# Thermoluminescence dating tests for lacustrine, glaciomarine, and floodplain sediments from western Washington and British Columbia

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To help further develop reliable procedures for accurate thermoluminescence (TL) dating of Quaternary waterlaid sediments, we tested TL dating procedures on sediment types rarely examined: six glaciolacustrine samples, three samples of glaciomarine drift, and eight samples of floodplain deposits. We used the partial-bleach (R-beta/gamma) technique applied to fine-silt polymineral grains. Results from our younger known-age glaciolacustrine sediments confirm earlier observations that only the clayey laminae are generally suitable for TL dating. A clayey lamina older than ca. 140–150 ka produced no age underestimation, and this result (ca. 300 ka) suggests that such older lake sediments are probably suitable for TL dating. Two proximal samples of glaciomarine drift produced large TL age overestimates, whereas the single distal glaciomarine-drift sample yielded an expected age (177 ± 38 ka), suggesting that follow-up studies are warranted. Our results for eight floodplain samples confirm that zeroing of light-sensitive TL is more likely to be effective for sediments deposited in quiet, ponded water on the floodplain than for proximal sediments deposited from turbid floodwater. TL age estimates for floodplain sediments of the regional Whidbey Formation are consistent with its expected last-interglacial age, and those for two samples from stratigraphically older beds are consistent with deposition near or beyond 200 ka. Two of our younger samples (one lacustrine and one floodplain) gave TL age underestimates, perhaps because of use of ultraviolet TL emissions for these samples.

Ayant pour objectif de faire progresser le développement de méthodes fiables de datation précise par thermoluminescence (TL) de sédiments subaquatiques quaternaires, nous avons testé les méthodes de datation par TL appliquées à des types de dépôts sédimentaires rarement étudiés : six échantillons de dépôts glaciolacustres, trois échantillons de drift glaciomarin et huit échantillons de dépôts de plaine d'inondation. La technique d'évanescence partielle (R-beta/gamma) a été appliquée à des grains de limon fin de composition pluriminéralogiques. Les résultats pour nos sédiments glaciolacustres reconnus comme étant les plus jeunes confirment les données obtenues antérieurement, ce qui indique, qu'en général, les laminites argileuses représentent un matériau approprié pour la datation par TL. Une laminite argileuse, plus vieille que ~140–150 ka, n'a pas donné un âge sous-estimé, et ce résultat (~300 ka) suggère que ce type de sédiments plus âgés est probablement approrié à la datation par TL. Deux échantillons proximaux de drift glaciomarin ont fourni des âges TL fortement surestimés, tandis que l'unique échantillon de drift glaciomarin a donné l'âge appréhendé (177 ± 38 ka), ce qui indique que la poursuite des études était justifiée. Nos résultats sur les huit échantillons de dépôts de plaine d'inondation confirment que la mise à zero de la TL photosensible semble être plus efficiente dans le cas des sédiments déposés sur la plaine d'inondation, en eau tranquille dans des étangs peu profonds, que pour les sédiments proximaux déposés dans les eaux turbides des débordements. Les âges TL déterminés pour les sédiments de dépôts de plaine d'inondation de la Formation de Whidbey, d'étendue régionale, sont compatibles avec l'âge estimé attribué au dernier interglaciaire, et les âges des deux échantillons des strates plus anciennes sont compatibles avec la période correspondant au dépôt des sédiments, il y a 200 ka, ou au-delà de cette date. Deux de nos échantillons les plus jeunes (un d'origine lacustre et l'autre de plaine d'inondation) fournissent des âges TL sous-estimés, peut-être parce que nous avons utilisé pour ces échantillons les émissions TL dans l'ultraviolet.

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## Introduction

Few geochronometric techniques exist for Quaternary sediments younger than the Brunhes–Matuyama geomagnetic field reversal event (780 ± 10 ka, Baksi et al. 1992; Spell and McDougall 1992) and older than the usual upper limit (35–40 ka) of the radiocarbon ($^{14}C$) dating method, unlike for deposits in most other geological periods. Thermoluminescence (TL) and the newer optically stimulated luminescence (OSL) sediment-dating techniques (Wintle and Huntley 1982; Aitken 1985; Huntley et al. 1985) have the potential to provide direct ages for detrital grains within a variety of Quaternary deposits that are undatable by other means, either because these deposits are older than 35–40 ka or because they lack material suitable for other dating methods.

Among the useful deposits for TL dating are volcanic ash and most unheated sediments. Zeroing of TL in volcanic glass shards is by heat, and is total, so that tephra can yield accurate TL ages up to ca. 400 ka (Berger 1991, 1992). In comparison, zeroing of the TL in the common detrital quartz and feldspar grains of unheated sediments is by daylight exposure and is incomplete. The potential impact of TL dating of detrital quartz and feldspar on the chronology of Quaternary glaciations is immense, provided the problem of incomplete zeroing by sunlight in certain types of sediment and of instability of certain mineral TL can be overcome.

Grains in loess are normally well exposed to light prior to deposition (Aitken 1985; Berger 1990; Wintle 1990) and the resetting of TL and its stability in such sediments appear consistent enough to permit reliable TL dating up to ca. 800 ka (Berger et al. 1992). Fine-sand-size (100–300 μm) quartz grains in eolian dune deposits are also good candidates for TL dating, and accurate ages up to ca. 600 ka have been produced (Huntley et al. 1993). On the other hand, the resetting of TL in various types of waterlain and glacial sediments is more complex, depending upon the minerals and their exposure to light just prior to deposition (Berger 1990).

Sediment dating by OSL has the *potential* advantage over TL of nearly complete zeroing of the measured signal by daylight exposure, for eolian deposits at least (Aitken 1992; Wintle 1993), but has the disadvantage of lacking an internal test for isolation of long-lived-signal components from short-lived components introduced by laboratory ionizing irradiations and other

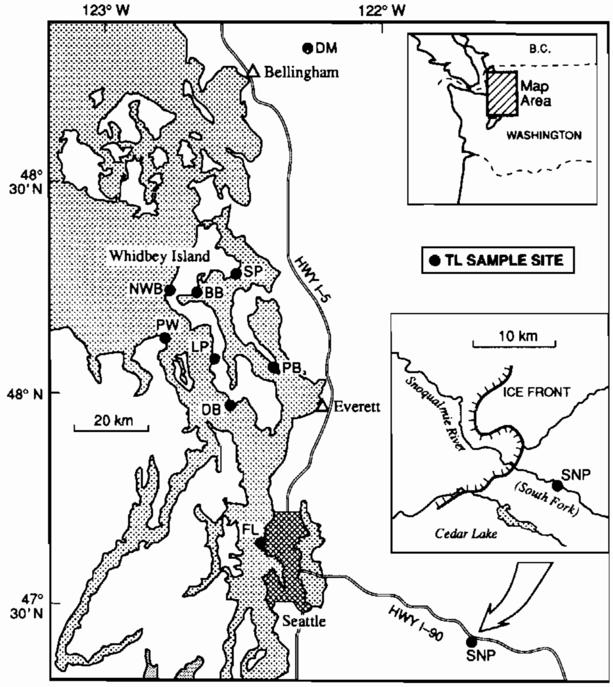


FIG. 1. Map of the Puget Lowland in western Washington state, U.S.A. Sites, from north to south: DM, Cedarville (DEMG samples); SP, Strawberry Point; NWB, North of West Beach; BB, Blowers Bluff; PW, Point Wilson; LP, Lagoon Point; PB, Pebble Beach; DB, Double Bluff; FL, Fort Lawton; SNP, Snoqualmie Pass.

treatments. Furthermore, although there have recently been many successful tests of accuracy of OSL dating of eolian sediments, there have been no reported systematic studies of OSL dating of waterlain deposits, nor has there yet been a published demonstration of OSL dating accuracy for sediments (eolian or otherwise) older than 50–60 ka (e.g., Berger 1993). As an example that OSL dating may provide no panacea for all difficulties of TL dating of waterlain sediments, Mangerud and Svendsen (1992) reported OSL ages from Holocene and modern beach–foreset sands that are several thousand years too old. Furthermore, for pre-Holocene samples they observed variations of more than 50 ka among ages determined from individual samples from the same formation.

We have used TL sediment-dating procedures here in a reconnaissance fashion, extending application tests to a wider variety of sediments than usual, and exploiting the proven capability of TL dating procedures to isolate long-lived-signal components (using the equivalent-dose plateau test) and to deal with incomplete zeroing of signal in some subaqueous depositional environments.

Because the Quaternary sedimentary record contains deposits laid down in a wide variety of depositional environments, determination of the reliability of TL ages from sediments of many origins is highly desirable. The Quaternary sediments of Washington include deposition in diverse environments, and span a time range of a few thousand years to more than 800 ka (Easterbrook 1986). Some of these are dated by $^{14}C$, others by fission-track, paleomagnetic, or amino acid methods. To help develop routinely reliable procedures for accurate TL dating of sediments, we tested TL sediment-dating procedures using "known-age" sediments representing lacustrine, glaciomarine, and floodplain depositional environments from Washington and British Columbia. These experiments with sediments ranging in expected age from ca. 13 to ca. 200 ka test both the zeroing assumption (by subaqueous exposure to daylight) and the long-term-signal stability of TL in sediments from this region. Some of our TL ages have already been reported (Easterbrook et al. 1992).

## Previous relevant TL dating work

*Lacustrine*

Several tests with independently dated and modern lacustrine sediments have been reported (e.g., Berger 1988 and references therein, 1990; Berger et al. 1987*a*; Forman 1989). The work of Berger shows that the most effective zeroing of light-sensitive TL occurs during slow deposition by rainout, and that, therefore, rhythmites containing a rainout horizon (clay-rich lamina) are preferred. Furthermore, ice-proximal lacustrine sediments have been shown (e.g., Berger 1988; Berger et al. 1987*a*) to yield age overestimates many times the expected ages, indicating ineffective natural TL zeroing in an ice-proximal depositional environment.

*Glaciomarine*

Few TL dating tests have been reported for glaciomarine sediments. In studies of modern and Holocene samples, Forman (1990) and Jennings and Forman (1992) showed that zeroing of light-sensitive TL is ineffective within ~1 km of an ice front. TL dating studies of lagoonal and nearshore marine sediments are perhaps relevant, and these (Berger 1990; Berger et al. 1990, 1991; Berger and Hanson 1992; Forman et al. 1987) show effective zeroing of light-sensitive TL by low-energy ambient light (wavelengths 500–700 nm).

*Floodplain*

Some known-age (modern and Holocene) silty floodplain sediments have been tested for TL dating suitability. Berger (1990, Fig. 24) observed little or no zeroing of light-sensitive TL in a sample of modern overbank silt collected within 200 m of the main fluvial channel. On the other hand, Berger et al. (1990) measured expected ages for Holocene organic silts from the Fraser River floodplain. In the latter samples, the presence of plant detritus and organic remains indicated slow deposition or bioturbation sufficient to allow effective zeroing of the light-sensitive TL in the 4–11 $\mu$m feldspar grains.

## Geological setting of samples

Because our objectives are to compare TL ages with independent age estimates for three classes of depositional environments, we outline here the independent ages and the evidence for the genetic interpretation of some of the deposits, especially where this information is otherwise not readily accessible. We reanalyzed two known-age glaciolacustrine samples from British Columbia and collected 15 additional samples (4 lacustrine, 3 glaciomarine, and 8 floodplain) from the Puget Lowland of western Washington (Fig. 1; Table 1). The general stratigraphy of the Puget Lowland is outlined in Fig. 2. As discussed in Clague et al. (1992), the indicated chronology for deposits older than ca. 40 ka is tentative, but it is sufficient for our "reconnaissance" field test of TL sediment-dating procedures in this region.

*Lacustrine*

Two glaciolacustrine samples from British Columbia that gave expected ages in a previous TL dating study (Berger et al.

TABLE 1. Samples and expected ages

| Sample | Location | Reference[a] | Expected age (ka)[b] |
|---|---|---|---|
| | **Lacustrine** | | |
| QNL84-3,5 | 0.3 cm silty clay lamina in rhythmites, Quesnel, British Columbia | 1 | 12.5±1.0 |
| WL84-5 | 10 cm silty clay bed, Williams Lake, British Columbia | 1 | 22±2 |
| SNOP-2s | 0.6 cm silty lamina in rhythmites, 9 m from bluff top, South Fork of Snoqualmie River (Fig. 1) | 2 | 15.6±0.5 |
| SNOP-2c | 1 cm silty clay lamina subadjacent to SNOP-2s | 2 | 15.6±0.5 |
| STRB-1 | Silt with clay, 90 cm below peat and 1.2 m above peat, Strawberry Point, Whidbey Island (Fig. 3) | 3 | 24–29 |
| LAGPT-1 | Two 1 cm silty clay laminae in rhythmites, Lagoon Point, Whidbey Island (Figs. 4, 5) | 3 | 150–200 |
| | **Glaciomarine** | | |
| DEMG-1 | 53 cm below 8 cm peat, clayey unit, Everson section, east end of Smith Road, Whatcom County (Fig. 6) | 3 | 14.5±0.5 |
| DEMG-7 | 125 cm below 8 cm peat, clay–sand–pebble unit (Fig. 6) | 3 | 14.5±0.5 |
| DUBLF-1 | Middle of silt unit without drop pebbles, Double Bluff, Whidbey Island (Fig. 7) | 3 | 150–200 |
| | **Floodplain** | | |
| DEMG-3 | 6 cm overbank clay layer 50 cm above 8 cm peat, Everson section (Fig. 6) | 3 | 13.3±0.5 |
| FTLWT-1 | 0.5 m below high-tide level in massive grey silt, Fort Lawton bluffs, West Point, Seattle (Fig. 3) | 4 | 20–24 |
| LAGPT-6c | 0.4 cm silty clay lamina in rhythmite, Lagoon Point, Whidbey Island (Fig. 5) | 3 | 100±20 |
| BBLF-4 | 10 cm grey silty clay with thin peaty layers, 5 cm below 6 cm brown peat bed, Blowers Bluff, Whidbey Island (Fig. 8) | 3 | 100±20 |
| NWBCH-1 | Massive clay–silt 45 cm below 12 cm peaty clay, 1 km north of West Beach (Libbey Park), Whidbey Island | | 100±20 |
| PTWIL-1 | In 22 cm silty clay layer ~8 m above 1 m peat bed, Point Wilson, Whidbey Island (Fig. 8) | 3 | 100±20 |
| WDBLF-1 | 5–6 cm silty clay layer ~2 m above sea level, below massive till, western Double Bluff, Whidbey Island (Fig. 7) | 3 | 150–200 |
| PBCH-1 | 0.2 cm silty clay laminae in 50 cm clay–silt bed ~30 cm above sea level, Pebble Beach, Camano Island (Fig. 7) | 3 | 150–200 |

[a]1, Berger et al. (1987*a*); 2, Mackin (1941), Porter (1976), Porter and Carson (1971); 3, Easterbrook (1969), Blunt et al. (1987), Easterbrook (1992); 4, Mullineaux et al. (1965).

[b]Ages are based on $^{14}C$ ages converted to calendar years (Mazaud et al. 1991) or the estimates of Blunt et al. (1987), which are based on amino acid analyses of shell. Most $^{14}C$ ages are cited in Blunt et al. (1987) or references therein. The relevant $^{14}C$ age for the DEMG floodplain sample (DEMG-3 in Fig. 6) is 11 640 ± 275 BP (W-940 on wood in peat, Table 2 in Easterbrook 1969, and Fig. 19 in Easterbrook 1992); for the DEMG glaciomarine samples (DEMG-1 and DEMG-7) is 12 970 ± 280 BP (I-1447 on marine molluscs, Easterbrook 1969, 1992); and for the SNOP sample is 13 570 ± 130 BP (UW-35 on wood, Porter and Carson 1971). An age assignment of 150–200 ka is based on amino acid age estimates of 100 ± 20 ka for the Whidbey Formation and of 150–200 ka for the Double Bluff Drift (Blunt et al. 1987).

1987*a*) were chosen to permit comparison of results from present TL dating procedures with the earlier results. Sample QNL84-3,5 (Table 1) is from the top of a 1.5 m unit of silt and silty clay rhythmites near Quesnel, and represents deglacial lake sediments. Sample WL84-5 represents an ice-distal prodelta or delta-slope deposit near Williams Lake.

In Washington we collected one lacustrine sample stratigraphically just above the Vashon Drift (SNOP at site SNP, Fig. 1), one from the Olympia Nonglacial Interval (STRB-1 at site SP, Fig. 1), and one from rhythmites just beneath the Whidbey Formation (LAGPT-1 at site LP, Fig. 1). Sample SNOP-2 (Table 1) was collected to test the deduction of Berger (1985*a*, 1990) and Berger et al. (1987*a*) that only thin clayey lamina can always provide sufficiently zeroed light-sensitive TL for accurate dating. Here, unlike in those studies, the minimum distance of the rhythmite from the ice front is known (Fig. 1), from extensive mapping of drift limits of the Puget Lobe (Mackin 1941; Porter 1976). The age of this rhythmite sequence is inferred from a $^{14}C$ age of 13 570 ± 130 BP (UW-35; Porter and Carsen 1971) on a fragment of cedar wood collected by R.C. Ellis from the upper part of the sequence at the town of Garcia. The second lacustrine sample was collected at Strawberry Point (SP in Fig. 1; see also Table 1 and Fig. 3). Two $^{14}C$ ages from the peat just above the TL sample yield an

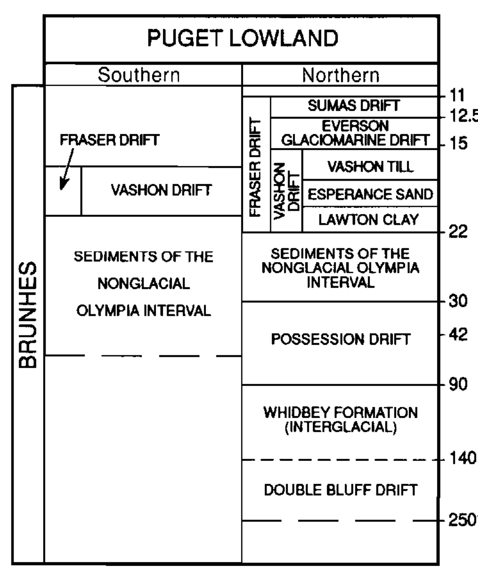


FIG. 2. Stratigraphic sequence in the Puget Lowland (after Blunt et al. 1987), but with a basal time boundary for the Whidbey Formation consistent with the presumed start of the last interglacial. Ages for the six youngest time boundaries are in calendar years, based on $^{14}C$ ages.

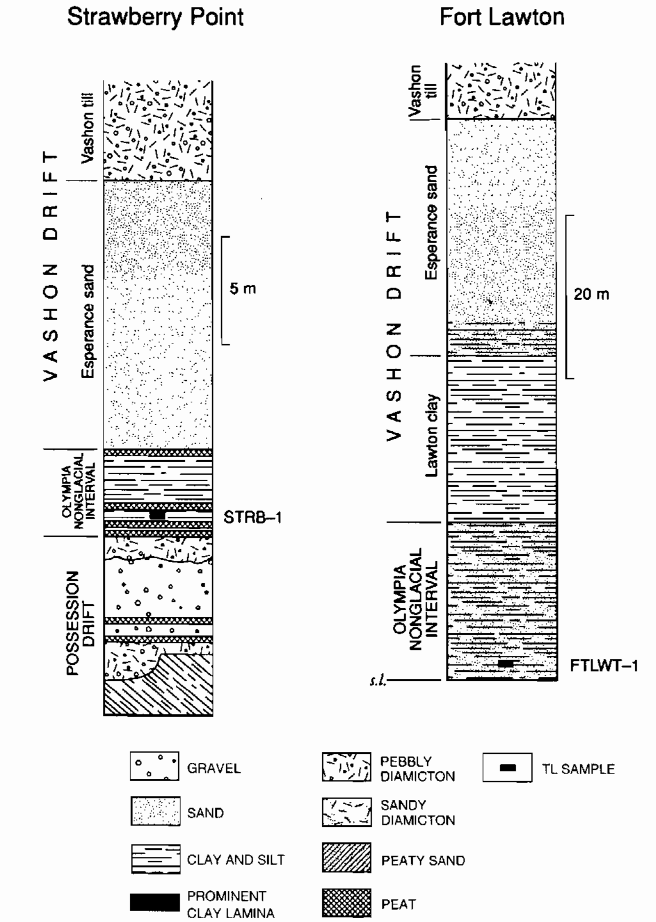


FIG. 3. Geological sections at two sites containing a lacustrine sample (STRB-1) and a floodplain sample (FTLWT-1).

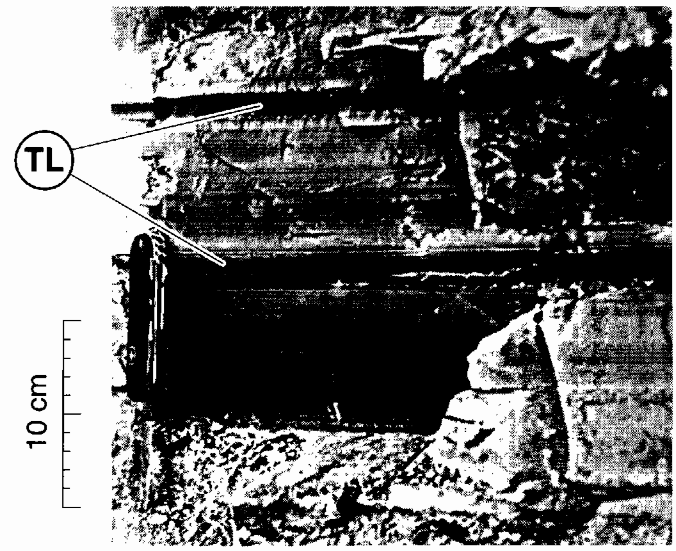


FIG. 4. Halftone image of two prominent clayey laminae (center and top) at sample LAGPT-1 site (Fig. 5). These two laminae were combined for TL measurements (Table 1). This gray, laminated, silty clay deposit dips northward and is overlain by stratified floodplain sand and silt of the Whidbey Formation.

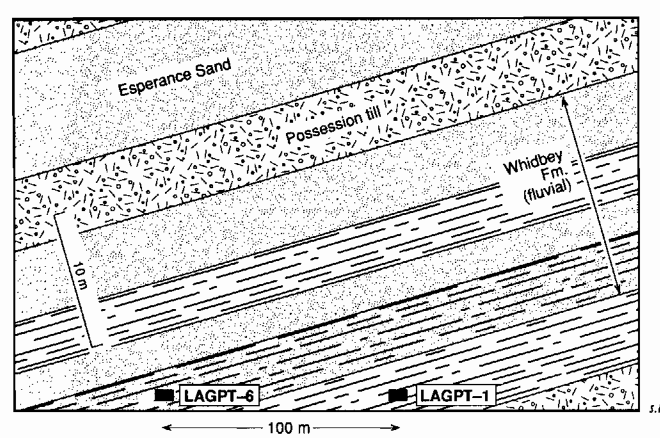


FIG. 5. Approximate geological profile section at Lagoon Point, showing location of both a floodplain sample (LAGPT-6) and a lacustrine sample (LAGPT-1).

average age of 22.70 ± 0.60 ka BP, and three results from the peat just below the TL sample average 24.80 ± 0.60 ka BP (Hansen and Easterbrook 1974).

In past tests of TL sediment dating, age underestimation has been commonly reported for samples thought to be older than ca. 100 ka (Berger 1988; Wintle 1990), and we are not aware of any such tests for lacustrine deposits of such antiquity. Therefore, we collected one sample from rhythmites at Lagoon Point (LP in Fig. 1) from beds beneath the Whidbey Formation and immediately overlying diamicton of the Double Bluff Drift (LAGPT-1 in Table 1 and Figs. 4 and 5). Although we assign an expected age of 150–200 ka to the Double Bluff Drift, this unit could be as old as 250 ka (Blunt et al. 1987; Fig. 2).

### *Glaciomarine drift*

We collected glaciomarine samples from both the type Everson Glaciomarine Drift near Deming (DEMG-1 and DEMG-7 at site DM, Fig. 1) and the type Double Bluff Drift on Whidbey Island (DUBLF-1 at site DB, Fig. 1).

#### *Everson type locality*

At its type locality, the Everson Glaciomarine Drift (Easterbrook 1963, 1992; Armstrong et al. 1965) consists of three members: two glaciomarine deposits separated by the nonmarine Deming sand (Fig. 6). Easterbrook (1992) speculates that refloated, once-stagnant, debris-laden ice could account for the near-contemporaneous deposition of such glaciomarine drift throughout the region. We collected two samples from the lower member in both a silty (DEMG-1) and silty sand (DEMG-7) component. Associated $^{14}C$ ages place deposition at 14.5 ka calendar years (Table 1).

#### *Double Bluff Drift*

The Double Bluff Drift (Easterbrook et al. 1967; Easterbrook 1968, 1992) consists of distinct members interpreted as till, glaciomarine drift, glaciofluvial sediments, and glaciolacustrine deposits, lying stratigraphically beneath the Whidbey Formation of the last major interglaciation in the Puget Lowland (Fig. 2). Except at Double Bluff (Figs. 1, 7) and Possession Point (southernmost tip of Whidbey Island), the Double Bluff Drift is rarely exposed in the central Puget Lowland, occurring elsewhere below sea level or beneath younger deposits.

The type section of Double Bluff Drift has been described by Easterbrook et al. (1967) (composite section shown in Fig. 7; see also Easterbrook 1968). Amino acid analyses of shells from glaciomarine drift at the type locality suggest an age of

111–178 ka based on leucine D/L ratios (Blunt et al. 1987). Amino acid ages of shells in Double Bluff glaciomarine drift elsewhere in the Puget Lowland suggest age ranges of 150–250 ka (Easterbrook and Rutter 1982; Easterbrook et al. 1982). The unit sampled for TL analysis crops out at the southeast end of Double Bluff (DUBLF-1 in Fig. 7 inset), where it consists of clayey, till-like layers interbedded with silt and pebbly silt.

Fossil marine shells and shell fragments occur in this glaciomarine drift. The shells are essentially in situ and indicate a marine environment. Elsewhere, barnacles attached to pebbles, fossils distributed from the top to the bottom of the deposits, articulated valves of shells, and absence of underlying fossiliferous deposits from which the fossils could have been derived by reworking demonstrate a glaciomarine origin. Barnacles, worm tubes, and other marine organisms occur still attached to glacially faceted and polished pebbles. Delicate ornamentation on some of the shells, including Foraminifera, has remained intact, and in some cases both valves of shells are still articulated. In some articulated shells, material inside the shells indicates that these organisms were living on the sea floor at the time of deposition of the ice-borne material, because normal till could not have been forced into the shells by a glacier riding over the sea floor.

These fossiliferous diamictons are generally characterized by a lesser degree of compaction than normal glacial till, presumably because these deposits never underwent appreciable glacial loading. According to the berg-ice hypothesis (e.g., Easterbrook 1992), after the main ice sheet receded from the portion of the lowland in question, the ice front remained nearby, and calving of the ice into the sea produced bergs carrying debris, which dropped to the sea floor as the bergs melted. Use of known depth habitation of certain living marine organisms represented by fossils in the glaciomarine drift allows an estimate of maximum water depths of 30–40 m during deposition.

All of these considerations suggest that some zeroing of light-sensitive TL could have occurred before final deposition, at least of the silt–clay members. The general occurrence of berg-dropped detritus in the drift could be considered evidence for deposition distal from any ice front (Boulton 1990; Gilbert 1990; Powell and Molnia 1989), though the complexity of depositional processes in modern siliclastic glaciomarine systems (Powell and Molnia 1989) favors caution in making this inference. However, several studies (e.g., Boulton 1990) suggest that ice-proximal deposition would produce dominantly unconsolidated mud.

*Floodplain*

Floodplain sediments were collected from (in order of expected antiquity) a fluvial unit separating two members of the Everson Glaciomarine Drift (DEMG-3 at site DM, Fig. 1), silt from the Olympia Nonglacial Interval (FTLWT-1 at site FL, Fig. 1), silty clay laminae and silt–clay horizons within the Whidbey Formation (LAGPT-6c at site LP, BBLF-4 at site BB, NWBCH-1 at site NWB, and PTWIL-1 at site PW, Fig. 1), and silty clay layers within the lower Double Bluff Drift (WDBLF-1 at site DB, PBCH-1 at site PB, Fig. 1).

*Two youngest samples*

Sample DEMG-3 (Table 1; Fig. 6) is thought to represent an overbank clayey horizon within the fluvial Deming sand. Sample FTLWT-1 (Table 1; Fig. 3) was collected just above mid-tide level in a massive silt member of the Olympia nonglacial deposits below the Lawton Clay Member of Vashon

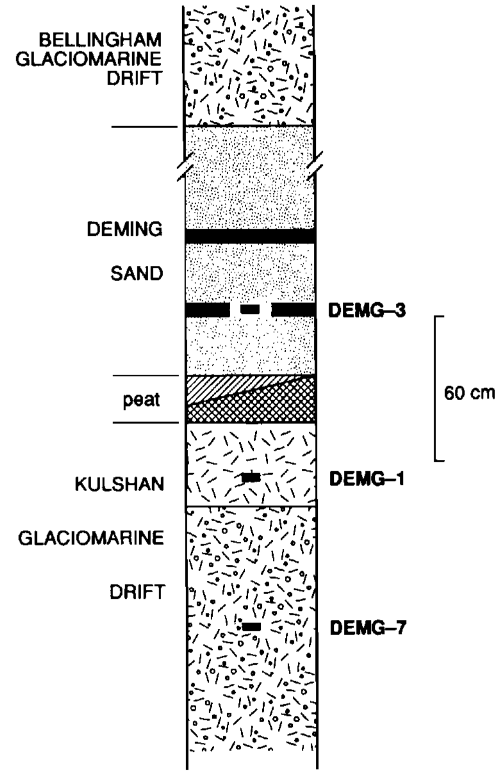


FIG. 6. Type locality of the Everson Glaciomarine Drift at Cedarville, containing an overbank sample (DEMG-3) and two glaciomarine samples (DEMG-1 and DEMG-7).

Drift at its type locality (FL in Fig. 1). During the Olympia Nonglacial Interval, floodplain and lacustrine silt, clay, and peat were deposited. At this site the unit below the Lawton Clay "shows evidence of having been deposited in a nonglacial environment of floodplains and shallow lakes" (Mullineaux et al. 1965). At this site $^{14}C$ ages range from 18.1 ka BP to 22.4 ka BP (Mullineaux et al. 1965), but elsewhere in the Seattle area and west of Seattle in Kitsap county wood and peat from nonglacial sediments immediately beneath Vashon till give $^{14}C$ ages as young as 15 ka BP (Mullineaux et al. 1965; Deeter 1979), or 17 ka calendar years. These younger ages indicate that the time-stratigraphic boundary at 22 ka (Fig. 2, based on $^{14}C$ ages from Strawberry Point in Fig. 1) is time transgressive.

*Whidbey Formation*

The sea cliffs 200–400 m east of Double Bluff (Fig. 7) were designated as the type section of the Whidbey Formation (Easterbrook et al. 1967). This formation consists mostly of sand interbedded with silt, clay, peat, and scattered lenses and beds of gravel. H.P. Hansen and Mackin (1949) interpreted similar sediments at Everett to be a result of "...very slow aggradation by meandering streams flanked by floodplain lakes and swamps." They thought that the lenticular coarse sands and gravels represented channel deposits and that the silty clay and peat were formed in floodplain lakes and swamps. All of the sediments included in the Whidbey Formation presumably were formed in such a depositional environment.

Analyses of pollen (representing trees such as lodgepole pine, balsam fir, Douglas fir, and western hemlock) from peat and silt indicate that the Whidbey Formation sediments were deposited during an interglacial period characterized by a warm

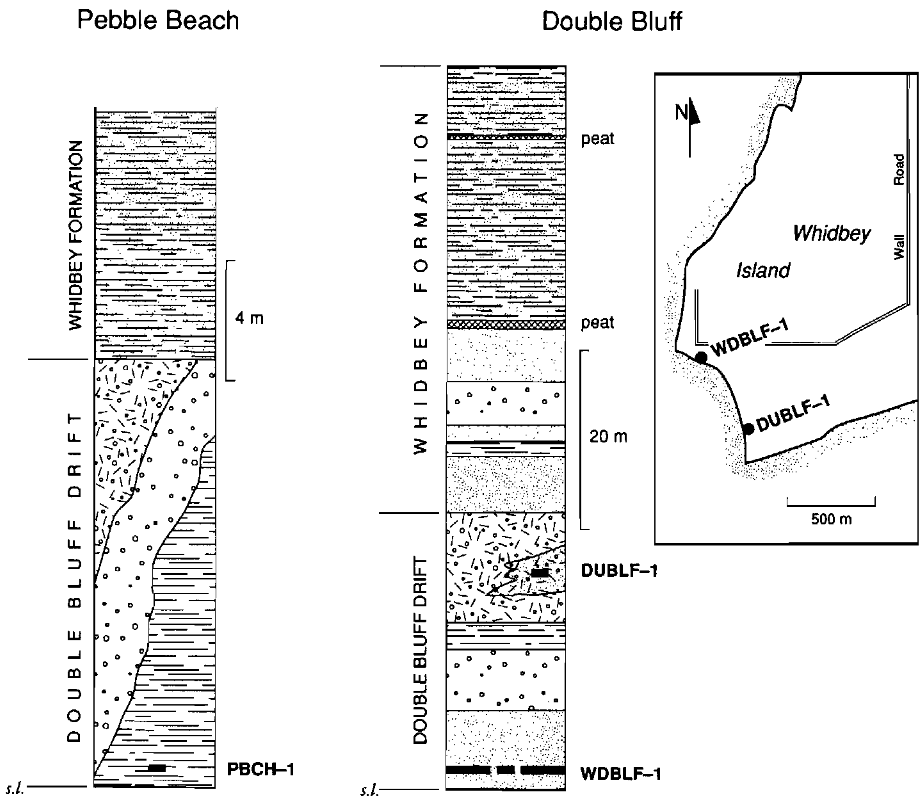


FIG. 7. Geological sections at two localities containing floodplain samples (PBCH-1 and WDBLF-1) and a glaciomarine sample (DUBLF-1). As implied in the inset map, the Double Bluff section is a composite from two sites.

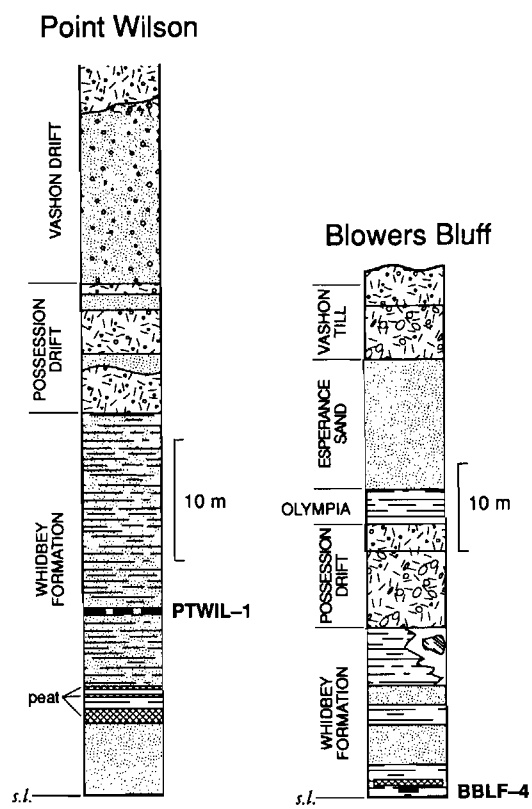


FIG. 8. Geological sections at two sites containing floodplain samples (PTWIL-1 and BBLF-4).

climate, but with cooler intervals at its beginning and end (H.P. Hansen and Mackin 1949; B.S. Hansen and Easterbrook 1974; Easterbrook et al. 1967; Heusser and Heusser 1981). More than 20 $^{14}C$ ages on wood and peat have produced only "infinite" ages (>33 ka BP to >49 ka BP) (Easterbrook 1969; Blunt et al. 1987). Amino acid analyses of wood and shells from the Whidbey Formation suggest an age of 100 ± 20 ka (Blunt et al. 1987).

We collected four samples of floodplain sediments from the Whidbey Formation (Table 1). From a rhythmitic silt sample (LAGPT-6, Fig. 5) 40–50 cm below a thick sand member we extracted a thin clayey lamina (LAGPT-6c, Table 1) for TL dating. At Blowers Bluff and Point Wilson (Fig. 8) we collected silty clay from 10 cm thick (sample BBLF-4) and 22 cm thick (sample PTWIL-1) beds. Sample NWBCH-1 (Table 1) was collected in a stratigraphic context similar to that of sample LAGPT-6 (Fig. 5).

*Double Bluff Drift*

Samples WDBLF-1 and PBCH-1 (Table 1; Fig. 7) represent the glaciofluvial–floodplain member of the Double Bluff Drift. Within the diamicton and underlying gravel of this drift are pebbles of distinctive granite and garnet schist that imply a source in British Columbia for both deposits. The gravel member and underlying silty member are therefore interpreted as proglacial outwash later overridden by the ice that deposited the diamicton (Easterbrook et al. 1967; Easterbrook 1992). H.P. Hansen and Mackin (1949) described a sequence of peat-bearing sand, silt, and clay 18–25 m thick above "sea level till and outwash" at Possession Point. A similar stratigraphic

TABLE 2. Dosimetry data

| Sample | Water[a] | $K_2O$ (wt.%) | $C_t$ $(ks^{-1} \cdot cm^{-2})^b$ | $C_{Th}$ $(ks^{-1} \cdot cm^{-2})^b$ | $b$ value $(pGy \cdot m^2)^c$ | Cosmic-ray dose rate $(Gy \cdot ka^{-1})^d$ | Dose rate $(Gy \cdot ka^{-1})^e$ |
|---|---|---|---|---|---|---|---|
| | | | | **Lacustrine** | | | |
| QNL84-3,5 | 0.20±0.10 | 2.27±0.02 | 0.511±0.013 | 0.178±0.027 | 0.817±0.080 | 0.12±0.03 | 3.04±0.29 |
| WL84-5 | 0.26±0.03 | 1.85±0.02 | 0.462±0.008 | 0.206±0.025 | 1.03±0.10 | 0.10±0.03 | 2.560±0.090 |
| SNOP-2s | 0.40±0.05 | 1.46±0.05 | 0.304±0.006 | 0.108±0.016 | 1.12±0.17 | 0.14±0.02 | 1.809±0.098 |
| | 0.15±0.05 | 1.21±0.06 | 0.319±0.030 | 0.122±0.020 | | | |
| SNOP-2c | 0.40±0.05 | 2.06±0.05 | 0.402±0.016 | 0.179±0.026 | 0.851±0.076 | 0.14±0.02 | 2.14±0.11 |
| STRB-1 | 0.25±0.05 | 1.56±0.05 | 0.391±0.008 | 0.174±0.025 | 1.0±0.2 | 0.12±0.02 | 2.20±0.13 |
| LAGPT-1 | 0.20±0.05 | 1.95±0.05 | 0.225±0.005 | 0.115±0.017 | 0.74±0.18 | 0.10±0.02 | 1.99±0.11 |
| | 0.20±0.05 | 1.46±0.05 | 0.264±0.006 | 0.102±0.017 | | | |
| | | | | **Glaciomarine** | | | |
| DEMG-1 | 0.30±0.05 | 1.36±0.05 | 0.252±0.006 | 0.083±0.014 | 0.83±0.15 | 0.14±0.02 | 1.611±0.084 |
| DEMG-7 | 0.25±0.05 | 0.84±0.08 | 0.27±0.03 | 0.087±0.015 | 0.83±0.15 | 0.14±0.02 | 1.37±0.11 |
| DUBLF-1 | 0.25±0.05 | 1.35±0.05 | 0.274±0.007 | 0.089±0.017 | 1.19±0.18 | 0.10±0.02 | 1.78±0.10 |
| | | | | **Floodplain** | | | |
| DEMG-3 | 0.35±0.05 | 1.59±0.05 | 0.368±0.015 | 0.094±0.015 | 0.91±0.11 | 0.14±0.02 | 1.86±0.10 |
| | 0.35±0.05 | 1.33±0.05 | 0.285±0.035 | 0.048±0.010 | | | |
| FTLWT-1 | 0.25±0.05 | 1.20±0.05 | 0.304±0.007 | 0.092±0.017 | 0.873±0.084 | 0.12±0.02 | 1.690±0.088 |
| LAGPT-6c | 0.40±0.05 | 3.02±0.05 | 0.433±0.009 | 0.181±0.027 | 1.05±0.69 | 0.12±0.02 | 2.74±0.26 |
| | 0.30±0.05 | 1.37±0.05 | 0.445±0.009 | 0.175±0.027 | | | |
| BBLF-4 | 0.40±0.05 | 2.05±0.05 | 0.421±0.008 | 0.153±0.023 | 0.834±0.093 | 0.10±0.02 | 2.081±0.097 |
| | 0.30±0.05 | 1.17±0.05 | 0.350±0.008 | 0.129±0.021 | | | |
| NWBCH-1 | 0.30±0.05 | 2.63±0.05 | 0.599±0.013 | 0.272±0.043 | 1.40±0.23 | 0.12±0.02 | 3.55±0.21 |
| PTWIL-1 | 0.32±0.05 | 3.40±0.10 | 0.641±0.010 | 0.299±0.032 | 0.97±0.15 | 0.12±0.02 | 3.58±0.19 |
| | 0.25±0.05 | 1.77±0.10 | 0.564±0.040 | 0.271±0.035 | | | |
| WDBLF-1 | 0.25±0.05 | 1.93±0.05 | 0.286±0.006 | 0.115±0.018 | 1.33±0.21 | 0.12±0.02 | 2.22±0.13 |
| | 0.25±0.05 | 1.66±0.15 | 0.270±0.010 | 0.110±0.010 | | | |
| PBCH-1 | 0.25±0.05 | 1.64±0.05 | 0.325±0.007 | 0.115±0.019 | 0.82±0.25 | 0.12±0.02 | 2.03±0.13 |

NOTE: The data for samples QNL84-3,5 and WL84-5 are from Berger et al. (1987*a*). Second row of data for some samples represents the surrounding sediment (when different from TL sample), and was used to calculate the gamma dose-rate component. Sample SNOP-2c shares the second row of sample SNOP-2s for the gamma component. Uncertainties here and elsewhere are $\pm 1\sigma$.

[a]Ratio of weight of water to weight of dry sample. We used the average of the collected value and the measured saturation value, most samples being near saturation when collected.

[b]Total count rate ($C_t$) and thorium count rate ($C_{Th}$) from finely powdered samples for thick-source alpha particle counting method (Huntley and Wintle 1981), except sample SNOP-2c, which was made into a glass disc (Huntley et al. 1986) prior to counting. Uranium count rate $C_U = C_t - C_{Th}$.

[c]Alpha effectiveness factor (Huntley et al. 1988; Berger 1988). The value for sample STRB-1 is estimated; it was not measured for this sample.

[d]Estimated from the data of Prescott and Hutton (1988).

[e]Calculated with the equations and conversion factors given by Berger (1988), and includes the cosmic-ray component.

sequence more than 60 m thick is well exposed in the 1.5 km long sea cliff exposures between Double Bluff and Useless Bay (just east of locality DB in Fig. 1). At Pebble Beach (PB in Fig. 1) the sampled clay–silt horizon has very fine parting and a few thin silty clay laminae. The total thickness of the clay–silt unit is ~8 m, and this unit is overlain by outwash gravel grading northwesterly into deformed gravel and compact diamicton that thickens northwesterly to ~10 m.

## TL dating procedures

The last exposure to daylight can be dated by TL methods (Aitken 1985). Daylight empties light-sensitive electron traps (e.g., lattice-defect sites), and after burial natural ionizing radiations repopulate emptied traps. In the laboratory, traps are again emptied, by heating now, with electron-hole recombination producing thermoluminescence. When the TL is related to an "equivalent dose" ($D_E$) by use of calibrated laboratory radiation sources, and an effective radiation dose rate is measured in separate experiments, then TL age = $D_E$/(effective dose rate). Common units are grays (1 Gy = 1 J/kg) for $D_E$ and Gy/ka for dose rate.

We used thick-source alpha-particle counting (Huntley and Wintle 1981) to measure U and Th concentrations in dried, finely powdered samples and commercial atomic absorption spectrophotometry to measure K concentrations. These data were combined with estimates of average cosmic-ray dose rate (Prescott and Hutton 1988) and an estimate of past average water content in the sample and surrounding deposits (Table 2) to yield an effective dose rate, using the conversion factors of Berger (1988).

Special care is needed in measuring estimates of $D_E$ in water-laid sediments (Berger 1988, 1990). Because the color and time-integrated intensity of natural light in sediment-laden water columns greatly affect the degree to which light-sensitive TL in sample-dominant feldspars is reset during transport before

TABLE 3. TL ages

| (1) Sample | (2) Bleach[a] | (3) Preheat[b] | (4) Filter[c] | (5) $D_E$ (Gy)[d] | (6) Temperature (°C)[e] | (7) Dose rate (Gy · ka$^{-1}$)[f] | (8) TL age (ka) | (9) Expected age (ka) |
|---|---|---|---|---|---|---|---|---|
| | | | | **Lacustrine** | | | | |
| QNL84-3,5 | 560/1 h | 75°C/8 d | UG11 | 78±21 | 280–300 (NP) | | | |
| | 560/1 h | 110°C/4 d | UG11 | 45.7±9.3 | 270–320 | 3.04 ±0.29 | 15.0±3.4 | 12.5±1.0 |
| WL84-5 | 560/1 h | 75°C/8 d | UG11 | 83±16 | 270–320 | | | |
| | 560/2.4 h | 110°C/4 d | UG11 | 80±13 | 270–330 | | | |
| | | | | 81±14[g] | | 2.560±0.090 | 31.6±5.7 | 22±2 |
| SNOP-2s | 560/24 h | 75°C/8 d | UG11 | 267±63 | 290–330 | 1.809±0.098 | 148±36 | 15.6±0.5 |
| SNOP-2c | 560/48.5 h | 75°C/8 d | UG11 | 39.3±4.0 | 270–320 | 2.14±0.11 | 18.4±2.1 | 15.6±0.5 |
| STRB-1 | 560/24 h | 75°C/8 d | UG11 | 42.6±3.8 | 290–330 | | | |
| | 560/24.5 h | 120°C/4 d | UG11 | 45.5±4.2 | 290–340 | | | |
| | | | | 43.8±1.4[h] | | 2.20±0.13 | 19.9±1.3 | 24–29 |
| LAGPT-1 | 560/48 h | 110°C/4 d | UG11 | 640±200 | 310–350 (?P) | 1.99±0.11 | 320±100 | 150–200 |
| | ADD | — | — | 766±86 | 330–400 (?P) | — | 380±50 | 150–200 |
| | | | | **Glaciomarine** | | | | |
| DEMG-1 | 560/2.5 h | 75°C/8 d | UG11 | 158±64 | 280–320 | | | |
| | 560/48 h | — | — | 180±31 | 290–330 | | | |
| | | | | 169±46[g] | | 1.611±0.084 | 105±29 | 14.5±0.5 |
| DEMG-7 | 560/24 h | 75°C/8 d | UG11 | 277±83 | 290–330 | 1.37±0.11 | 202±63 | 14.5±0.5 |
| DUBLF-1 | 560/72 h | 110°C/4 d | UG11 | 315±65 | 300–340 | 1.78±0.10 | 177±38 | 150–200 |
| | | | | **Floodplain** | | | | |
| DEMG-3 | 560/1 h | 75°C/8 d | UG11 | 104±28 | 280–330 | | | |
| | 560/24 h | — | — | 110±18 | 290–340 | | | |
| | | | | 107±23[g] | | 1.86±0.10 | 57±13 | 13.3±0.5 |
| FTLWT-1 | 560/2 h | 75°C/8 d | UG11 | 22.6±3.9 | 270–320 | 1.690±0.088 | 13.4±2.4 | 20–24 |
| | 560/49 h | — | — | 31.0±3.5 | 280–340 | — | 18.4±2.5 | 20–24 |
| LAGPT-6c | 560/72 h | 110°C/4 d | UG11 | 280±100 | 280–330 | 2.74±0.26 | 102±38 | 100±20 |
| | ADD | — | — | 380±110 | 310–400 | — | 138±42 | 100±20 |
| BBLF-4 | 560/48 h | 110°C/4 d | UG11 | 221±34 | 310–350 | 2.081±0.097 | 106±17 | 100±20 |
| NWBCH-1 | ADD | 110°C/4 d | BG28 | 505±19 | 300–320 (?P) | 3.55±0.21 | 142±10 | 100±20 |
| PTWIL-1 | 560/72 h | 110°C/4 d | BG28 | 540±150 | 270–340 | 3.58±0.19 | 151±43 | 100±20 |
| WDBLF-1 | 560/72 h | 110°C/4 d | BG28 | 640±160 | 320–360 (?P) | 2.22±0.13 | 289±74 | 150–200 |
| PBCH-1 | 560/72 h | 110°C/4 d | BG28 | 590±170 | 320–350 (?P) | 2.03±0.13 | 291±86 | 150–200 |

[a]In the format *A*/*B*, *A* specifies the approximate low cutoff wavelength (nm, at 10% threshold) of the optical-bleaching glass filters (arrangements $f_1$ and on-center $f_2$ of Berger (1990), corresponding to an irradiance of 245 $\mu$W/cm$^2$ or 880 mJ/(cm$^2$ · h)) and *B* gives the duration of the optical bleaching. The partial-bleach (PB) TL method was used throughout, but for comparison the $D_E$ value obtained from the additive-dose (ADD) procedure is given for some samples. The PB method gave no plateau for sample NWBCH-1, so only the result from the ADD procedure is listed.
[b]The temperature and storage interval for the pre-readout heat treatment for removing unstable TL in laboratory-irradiated subsamples. The dashes (—) in columns 3, 4, and 7 indicate identity with the overlying specification.
[c]The optical glass filter in front of the photomultiplier tube: Schott glass UG11 (2 mm thick, bandpass 270–380 nm, 10% threshold), Schott glass BG28 (bandpass 355–520 nm), both with a Schott glass heat-absorbing filter KG-3 (bandpass 300–820 nm). As well, a fused-silica neutral density filter (10% transmission) was used for all experiments.
[d]Single-row $D_E$ values are weighted mean ± average error (Berger and Huntley 1989) over the temperature interval in column 6. Sample weighted means use standard weighting by inverse variance.
[e]Interval used in column 5. Each $D_E$ value represents a 10°C slice of the glow curves (e.g., point 300°C represents 290–300°C), so that, for example, data points 320–350°C in a $D_E$ plot correspond to a 310–350°C glow-curve temperature interval. NP, no plateau, ?P, ambiguous plateau.
[f]See Table 2.
[g]Average $D_E$.
[h]Weighted mean $D_E$.

burial, we used the conservative recommendations of Berger (1990) for low-energy (~560–800 nm wavelengths) laboratory illumination (optical bleaching). This region of the light spectrum lies just on the low-energy side of the most persistent wavelengths in turbid water (Berger 1990).

We used a ~125 mCi (1 Ci = 37 GBq) $^{90}$Sr–$^{90}$Y source for beta irradiations and $^{241}$Am sources for alpha irradiations, for the respective determinations of $D_E$ values and of alpha-efficiency values (Table 2). The $^{60}$Co gamma source at Simon Fraser University (Huntley et al. 1993) was used for some samples. We used the partial-bleach (R-beta/gamma) procedure (Aitken 1985) to measure $D_E$ values, which were then plotted against readout temperature to provide a plateau test (Aitken 1985). To remove thermally unstable and anomalous-fading TL components from the laboratory-irradiated subsamples prior to TL readout, we used high-temperature storage treatments as practiced by Berger (1987) and Berger et al. (1992). Different treatments were tested on younger samples before a particular

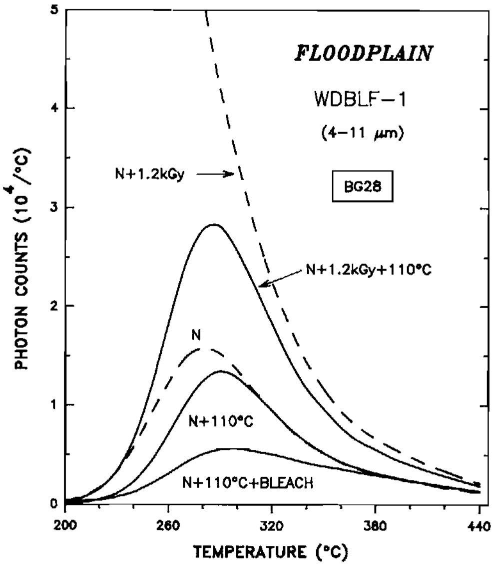


FIG. 9. Smoothed representative glow curves for sample WDBLF-1. Readout at 5°/s through a blue-pass BG28 glass filter. N, untreated; N+1.2kGy, N with added laboratory dose of 1200 Gy; N+1.2kGy+110°C, same after preheating at 110°C for 4 days; N+110°C, N after preheating; N+110°C+BLEACH, same after optical bleaching for 3 days with wavelengths <560 nm blocked (Table 3).

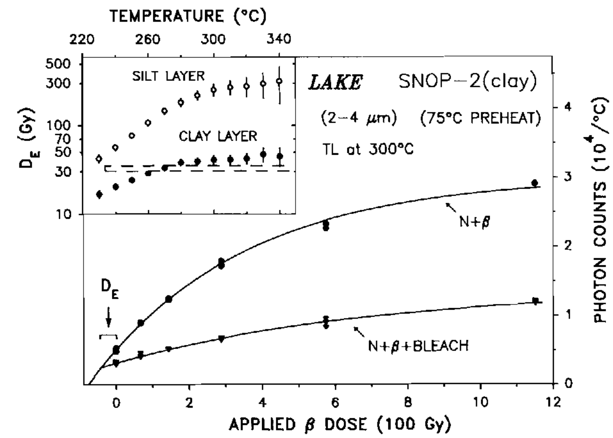


FIG. 10. Partial-bleach TL dose-response curves and intercept $D_E$ value at the 290−300°C slice of the glow curves for the clay-lamina subsample of SNOP-2. For this subsample the 2−4 μm size fraction was used; the 4−11 μm fraction was employed for all other samples. Here and below, the bleaching conditions for the lower curve are specified in Table 3. Weighted saturating-exponential regression was used (Berger et al. 1987*b*). At least two points are represented at each dose point on each curve, with five or six points at zero applied dose. Intercept $D_E$ values for this clay lamina and adjacent silty lamina are plotted in the inset against glow-curve temperatures (the intercept $D_E$ plateau test). In the inset, the thickness of the box outlined by the broken line represents the $\pm 1\sigma$ range of expected $D_E$ values for the clay lamina. The expected $D_E$ values for the silt lamina would be somewhat less (compare ratio of dose rates in Table 2). Here and below, error bars represent $1\sigma$ analytical uncertainty.

storage treatment was chosen for older samples. TL age estimates and their main contributing parameters are listed in Table 3.

An illustration of the effects of such pre-readout heat treatments on untreated (N) and laboratory-irradiated (N+1.2kGy) subsamples is given in Fig. 9. Here, a 4 day storage at 110°C has removed a significant component of unstable TL from the irradiated subsample. Other tests (Berger and Eyles 1993) show that such preheating removes as much (but no more) TL as decays at room temperature during 1 year. This phenomenon has been discussed at length elsewhere (Berger 1987, 1988). Figure 9 also shows the partial reduction in TL due to a 3 day optical bleaching with low-energy light.

## Discussion

As this is a report of a test application of a dating technique, rather than a geochronological application to local stratigraphic problems, we classify our discussion of results according to general sediment type, instead of according to age range or stratigraphic problem.

Note that most of our experiments were performed before the recent observations of Balescu and Lamothe (1992) and Berger et al. (1992) of sometimes significant TL age underestimation due to use of ultraviolet (uv) TL emissions (passed by filter UG11 here). Four of our samples were analyzed with use of the recommended blue TL emissions (passed by filter BG28 here), and we comment below on the significance of this matter for our results. We emphasize that the causes of this uv age-underestimation effect are not yet understood, but Berger (1994) discusses some plausible hypotheses. Nevertheless, this empirical observation can serve as a guide to suitable TL sediment-dating protocols.

### *Lacustrine*

One of the interesting observations of a TL dating study of known-age glaciolacustrine rhythmites from British Columbia (reviewed in Berger 1988) is that zeroing of light-sensitive TL is most effective in feldspar minerals within the clayey laminae and can be strikingly ineffective for the silty laminae. TL age estimates as much as five times the expected values were measured for some silty laminae. On the other hand, Berger (1990) observed more effective (but variable) zeroing in "zero-age" silty laminae from an alpine lake 10−15 km from present glacial meltwater sources. These differences in TL results between laminae type were attributed to differences in depositional processes, with the dominant rain-out from suspension ensuring more effective zeroing of TL in clayey laminae. The differences between results from silty laminae were attributed to different average transport distances from ice fronts. The fluvial transport distance of several kilometres in the study area of Berger (1990) presumably assured more effective TL zeroing than the more-ice-proximal origins of detritus in the silty laminae discussed by Berger (1988). To further test these observations, we collected sample SNOP, a known-age glaciolacustrine rhythmite deposited no closer than 6 km from the ice front bordering an ancestral lake (Fig. 1). The results (Fig. 10) confirm the dramatic differences reported earlier, and the suggestion of Berger (1985*a*) that only the clayey laminae are suitable for TL dating of rhythmites.

To attempt to date older waterlain sediments, we need to remove a greater fraction of laboratory-induced low-temperature TL than is removed by the 75°C (8 day) heat treatment used for sample SNOP (based on the practice of Berger 1987). The efficacy of using higher preheating temperatures depends on the assumption of a multitrap feldspar TL emission from our polymineral samples, as suggested by Wintle (1985). As the results of Berger et al. (1987*a*) for our two known-age samples from British Columbia (QNL84-3,5 and WL84-5) were obtained

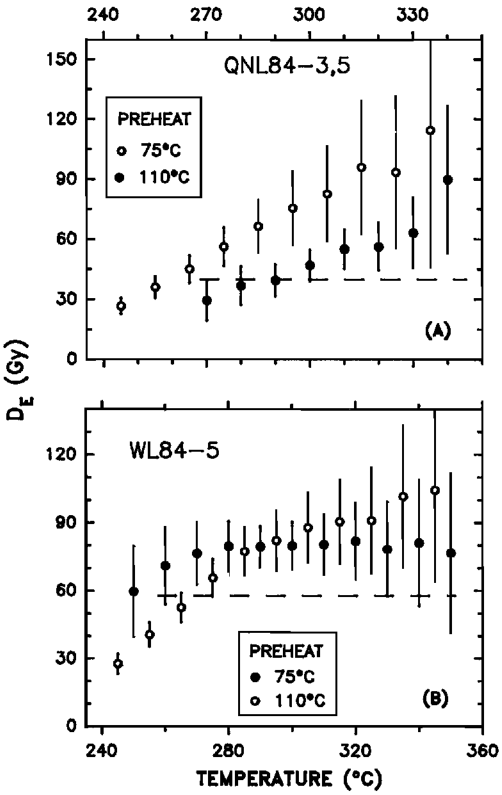


FIG. 11. $D_E$ plateau plots for two known-age glaciolacustrine samples, showing the effects of different preheating treatments. Here and below, $D_E$ values are sometimes plotted displaced ±5°C for clarity of viewing. Expected $D_E$ values are indicated by broken lines.

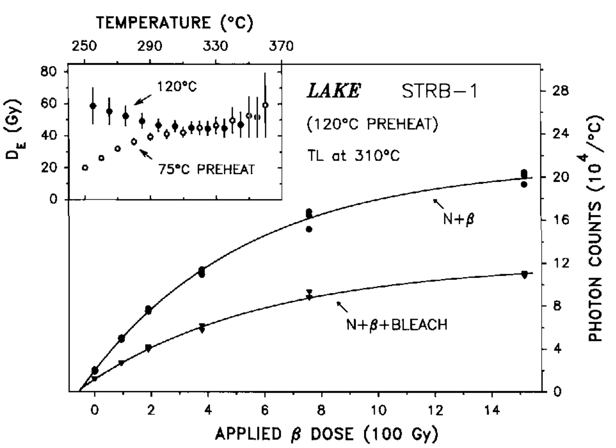


FIG. 12. Dose-response curves and $D_E$ plateau plots for sample STRB-1, showing (inset) the effect of different preheating treatments on the $D_E$ values.

without use of any preheating (only long storage), we tested two heat treatments for each of these. One of these treatments was the 75°C heating used by Berger (1987), who observed that it produced results equivalent to those arising from only long storage at room temperature.

The results for one experiment on sample QNL84-3,5 are perhaps barely satisfactory (Fig. 11A), whereas both experiments on sample WL84-5 (Fig. 11B) produced good $D_E$ plateaus. As also observed by Berger et al. (1987*a*), the TL

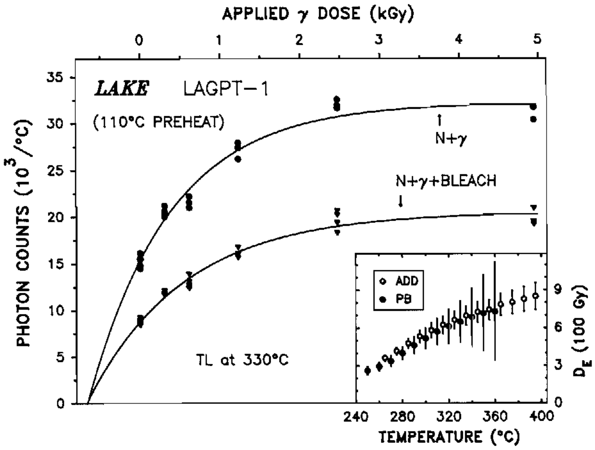


FIG. 13. Dose-response curves and the corresponding $D_E$ plateau plots (additive dose (ADD) and partial bleach (PB)) for sample LAGPT-1. The increasing errors in PB $D_E$ values at higher readout temperatures make recognition of a PB plateau difficult for such older samples (inset), and is a well-known consequence of the diminishing difference between the unbleached and bleached data at higher glow-curve temperatures (see also Fig. 9). Use of higher preheating temperatures could alleviate this problem somewhat (see text), but this problem can be expected to limit the upper age of reliable application of this TL dating procedure to waterlain deposits.

age estimate for sample WL84-5 (Table 3) seems somewhat older than the expected age. This could be an indication of ineffective zeroing of light-sensitive TL in this sample. Nevertheless, these results confirm the earlier results and indicate that a 110°C (4 days) preheating is an acceptable procedure. Similar comparisons with other sediments (Berger et al. 1992; Berger and Eyles 1993; Berger and Anderson 1994) and sample STRB-1 (Fig. 12) support this conclusion. We therefore employed the 110°C preheating for all older samples. Our results for sample STRB-1 underestimate the expected age by ~25% (Table 3). This is perhaps due to the use of uv emissions (filter UG11), which has been mentioned above, an interpretation that is readily testable with further work.

The only old rhythmite we analyzed (LAGPT-1) produced the expected saturation form of growth curves (Fig. 13) and appeared to yield an approximate partial-bleach plateau at the highest readout temperatures (inset Fig. 13). The corresponding TL age estimate of 300 ± 100 ka (maximum of 380 ± 50 ka indicated by the additive-dose (ADD) procedure) is higher than expected, but the large analytical uncertainty does not preclude agreement with the expected age (which is itself uncertain, as discussed above). This approximate plateau result is not unlike some results of Berger et al. (1991) that yielded expected ages. In spite of the unsatisfactorily large analytical errors in these partial-bleach $D_E$ values and the ambiguous plateau from this single-analysis result, the approximate agreement with the result from the ADD procedure and with the expected age is promising. This suggests that lacustrine sediments older than ca. 200 ka could be datable by these TL procedures, with the caveat that blue TL emissions (e.g., filter BG28) and higher preheating temperatures (e.g., 140–160°C for 2–4 days storage) are recommended.

### *Glaciomarine*

Both of the proximal glaciomarine samples (DEMG-1 and DEMG-7) yielded $D_E$ plateaus (hence, TL ages) far in excess

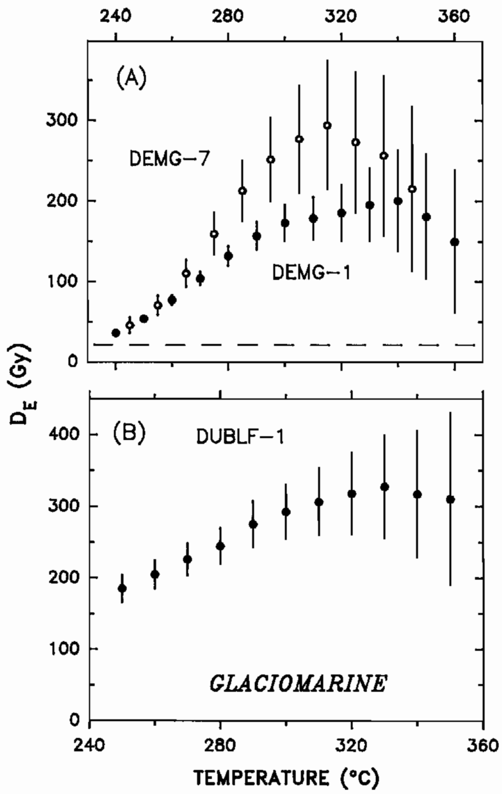


FIG. 14. $D_E$ plateau plots for two young known-age glaciomarine samples (A) and a >100 ka glaciomarine sample (B). Expected $D_E$ values are indicated by a broken line in A.

of the expected values (Table 1; Fig. 14A). These age overestimations are consistent with the expected ineffectiveness of zeroing of light-sensitive TL in ice-proximal depositional environments (Berger et al. 1987*a*; Jennings and Forman 1992). On the other hand, our single, old, glaciomarine sample (DUBLF-1) produced a TL age of 177 ± 38 ka that is consistent with the expected age (Table 1). We infer that some glaciomarine sediments are datable by present TL procedures, but that additional TL dating tests on such deposits are required. Perhaps systematic TL dating studies of modern glaciomarine sediments are needed to produce useful sample-selection guidelines for TL dating of such deposits. Certainly, samples older than ca. 100 ka could be datable. Use of blue TL emissions is recommended for such future TL studies.

*Floodplain*

Our results for young floodplain samples are erratic. The $D_E$ plateau values for overbank sample DEMG-3 greatly exceed the expected value (Fig. 15), whereas the TL age estimates for distal sample FTLWT-1 (13−18 ka) underestimate the expected age of 20−24 ka. The overestimation of $D_E$ values in Fig. 15 is consistent with the observation of Berger (1990, Fig. 24) that little zeroing of light-sensitive TL may occur in overbank deposits close to main fluvial channels and presumably deposited in energetic floodwaters. This contrasts with the observation of Berger et al. (1990) that effective zeroing can occur in floodplain sediments representing quiet-water deposition.

Our intention in the use of two quite different durations of optical bleaching for sample FTLWT-1 (Fig. 16) was to test for agreement of $D_E$ plateaus. As observed for sheetflow sediments (Berger 1985*b*), we would expect to measure higher

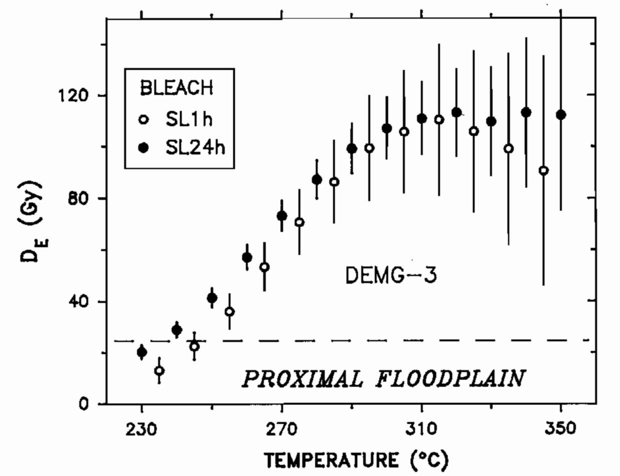


FIG. 15. $D_E$ plateau plot for sample DEMG-3, showing expected $D_E$ values (broken line).

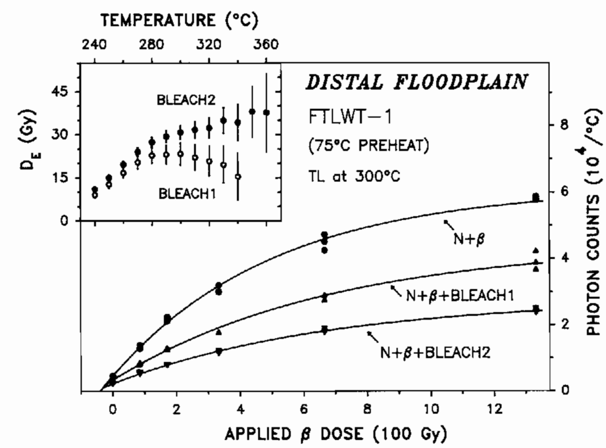


FIG. 16. Dose-response curves and $D_E$ plateau plots for sample FTLWT-1. BLEACH1, 2 h. BLEACH2, 49 h.

$D_E$ values at longer bleaching times if the light-sensitive TL was only partially reset at deposition, but we would expect concordant $D_E$ values if zeroing was as affective as implied for the floodplain samples of Berger et al. (1990). In any case, we would expect a minimum TL age to be given by the results from the shorter optical bleaching time. Although differences in $D_E$ plateau values (Fig. 16 inset) are consistent with only partial resetting of light-sensitive TL at deposition, the observed age underestimation (Table 3) corresponding to the shorter bleaching time has no evident explanation other than that this could be another example of the uv-emissions effect mentioned above. Future studies could readily test this hypothesis.

The TL age estimates for all older floodplain samples are consistent with the expected ages (Table 3) within 2$\sigma$ error limits. Perhaps the TL ages near 290 ka for samples WDBLF-1 and PBCH-1 are overestimates because of unrecognized ineffective zeroing (creating a laboratory "overbleaching" effect, Berger 1988), but the large TL analytical uncertainties coupled with the possibility that these sediments are actually as old as ca. 250 ka (Blunt et al. 1987) does not justify further speculation. Additional TL tests on independently dated floodplain sediments are needed to confirm the encouraging results we report for old floodplain deposits.

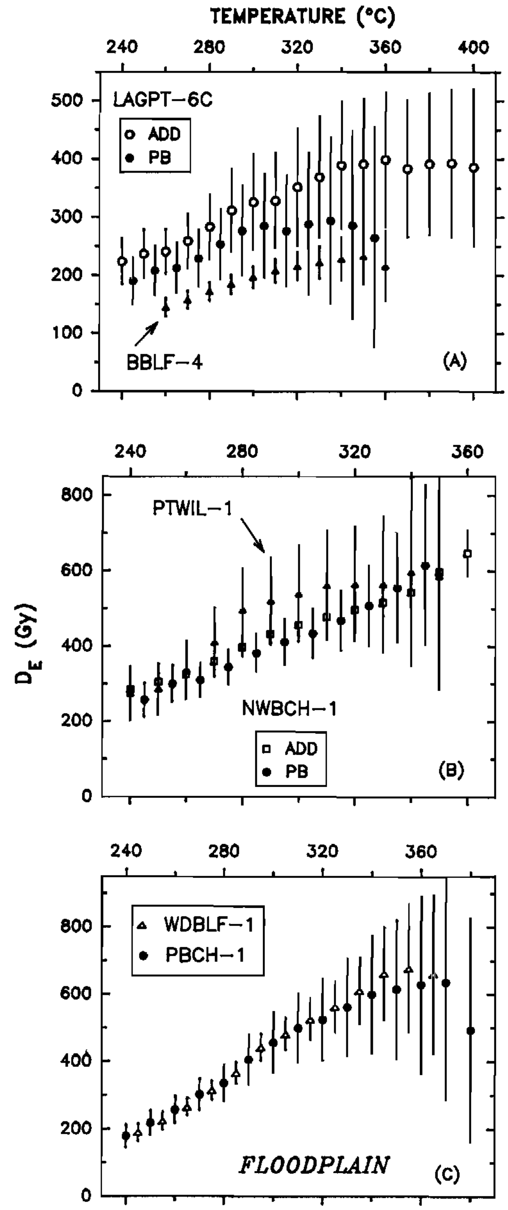


FIG. 17. $D_E$ plateau plots for the six oldest floodplain samples. For two samples, $D_E$ values from the additive-dose procedure (ADD) are shown to indicate the maximum permitted values (assuming removal of all unstable TL).

Reasonable plateaus in $D_E$ values are observed for all floodplain samples, except perhaps samples NWBCH-1 (ADD in Fig. 17B) and WDBLF-1 and PBCH-1 (Fig. 17C). For sample NWBCH-1 the $D_E$ values for the ADD procedure provide an upper limit to the allowable $D_E$ values, assuming all unstable TL has been removed. Use of higher preheating temperatures for these three poor-plateau samples might produce clearer plateaus, by removing a larger fraction of the unstable TL that causes the lowered $D_E$ values below 300°C of the glow curves (Berger and Anderson 1994). We note that the two youngest TL ages for these six samples (ca. 100 ka for samples LAGPT-6c and BBLF-4) were obtained with the use of uv TL emissions. Perhaps these TL ages would be slightly older if blue emissions were used, but the observed differences between the two classes of results are not statistically significant.

We conclude from these tests on older distal floodplain sediments that TL dating of such widespread Quaternary deposits is a very promising application. Future TL dating applications could benefit from use of blue emissions, higher pre-readout temperatures (e.g., 140–160°C (2–4 days)), and multiple TL dating analyses from a given horizon or local stratigraphic unit. Our results for these older floodplain sediments are consistent with the suggested chronostratigraphy of the region (Fig. 2), and imply that more detailed future TL dating applications could refine this chronostratigraphy.

## Conclusions

Tests on our younger known-age glaciolacustrine sediments confirm earlier observations that only the clayey laminae are likely to generally contain effectively zeroed light-sensitive TL. A single test of a clayey lamina older than ca. 140 ka indicates no age underestimation of the kind reported for $>100$ ka sediments from Europe (e.g., Wintle 1990), and provides promise that such older lake sediments can be accurately dated by TL methods, though further controlled TL dating studies are needed for such deposits.

Tests on three glaciomarine-drift samples produced large TL age overestimates for two of the samples and the expected age (177 $\pm$ 38 ka) for the third, from the Double Bluff Drift. The first two samples are considered to have been deposited close to ice fronts, because of the local terrain and conditions of ice retreat. On the other hand, the third sample was laid down in a marine environment probably distant from any active ice fronts. TL dating studies of modern siliclastic glaciomarine depositional environments could help establish objective field criteria for selection of samples that would have effectively zeroed light-sensitive TL.

We tested eight floodplain samples, and our results confirm earlier observations that overbank deposits laid down near fluvial channels are unsuitable for present TL dating procedures. On the other hand, fine-grain floodplain sediments believed to have been deposited in quiet, ponded water on the floodplain (e.g., oxbow lakes, abandoned channels, and associated marshes and swamps) appear to be good candidates for TL dating, up to at least 200 ka.

In light of the above encouraging results, similar application tests of OSL dating procedures would be warranted because OSL signals are more sensitive to daylight zeroing than are TL signals. However, as mentioned in the Introduction, demonstration of the accuracy of OSL dating has not yet been reported for *any* class of sediment older than 50–60 ka, unlike for TL methods, and zeroing of OSL in some depositional environments has been shown to be ineffective.

Our results for sediments from the regional Whidbey Formation are consistent with its expected last-interglacial age, and those for three samples from stratigraphically correlated units of the pre-last-interglacial Double Bluff Drift are consistent with deposition near or beyond 200 ka. In particular, the sample DUBLF-1 from the middle of the unit at its type locality or section of Double Bluff is probably ca. 180 ka old, but correlated basal beds near this section (WDBLF-1) and at the Pebble Beach site could be ca. 290 ka old. More detailed sampling and additional TL dating are needed to confirm these suggestions.

Finally, some of our younger samples yielded age underestimates consistent with similar effects reported elsewhere when uv TL emissions are used. Though the cause of this age-underestimation effect in fine silt grains is not yet understood, we recommend use of blue TL emissions for future TL fine-grain, polymineral, sediment-dating applications.

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