THERMOLUMINESCENCE (TL) DATING IN SEISMIC HAZARD EVALUATIONS: AN EXAMPLE FROM THE BONNEVILLE BASIN, UTAH

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ABSTRACT

Thermoluminescence (TL) of minerals is the release of light when grains are heated to 150°-500° C. As sediments are buried longer they progressively acquire more TL from accumulated radiation damage from α, β, γ, and cosmic radiation. If the total amount of radiation dose received can be calculated, and the current dose rate measured, then dividing the total dose by the yearly dose rate will yield a TL age. Total doses are calculated by heating the sample until all TL is released, then re-irradiating the sample in the lab with known doses until the natural TL is duplicated. Present dose rates are measured with radiometers. The TL age thus calculated is also a function of: 1) the amount of "residual" TL from previous erosion cycles, 2) the mean moisture content through time, 3) the radioactive component of transient groundwaters, and 4) a host of non-linear behaviors of TL with increasing dose. Typical standard errors are ± 10% of the quoted date.

Faulted and liquefied Lake Bonneville strata in Hansel Valley, UT, record a history of recurrent surface faulting which culminated in the 1934 M6.6 earthquake. Attempts to reconstruct the recurrence times of Quaternary faulting events was hindered by lack of carbonaceous material datable by ^{14}C methods. However, five TL dates from inorganic silty strata yielded dates from the Bonneville cycle (13 ka), an older lake cycle (76-82 ka), and from the Little Valley cycle (138 ka). The faulting history derived from these dates indicated multiple faulting from 138-82 ka, only one faulting event from 82-27 ka (near the later date), possibly one event between 21 and 15 ka, one event at 13 ka, and another in 1934 A.D. Temporal clustering of earthquakes during episodes with deep lakes (oxygen isotope stages 6 and 2) suggests that water loading of the crust stimulated surface faulting events.

INTRODUCTION

Determining the age of faulted Quaternary sediments which contain no material suitable for radiocarbon dating has always been a major problem in seismic hazard evaluation. Thermoluminescence (TL) dating of inorganic silts can potentially provide absolute dates on non-carbonaceous deposits as old as several hundred ka. However, in order to get the date assumptions must be made concerning: 1) the time of exposure to sunlight before redeposition to its present site, 2) whether the silt was re-deposited subaerially, or in shallow versus deep water, 3) the time-averaged moisture content of the sediment, 4) the radioactive component of transient groundwaters, and 5) the densification history of the sediment. In some ways this reconstruction of the recent history of the dated component is similar to that used for other materials (e.g., distinction between ancient carbon and more modern decayed roots), but the specific questions themselves are unique to the TL method.

This paper will describe briefly the physical principles of TL, how it has been used in the past, how sampling is performed, and what common problems arise in interpreting the dates. A case history from the northern Lake Bonneville basin of Utah will show how the interpretation of the dates is improved by accessory evidence from the sedimentology and paleoecology of the sediments.

PHYSICAL PRINCIPLES OF THERMOLUMINESCENCE

Emission of Radiation

Most sediments contain small quantities of ^{238}U, ^{232}Th, and ^{40}K. The radioactive decay of these isotopes and their daughter products releases α, β, and γ radiation into the surrounding sediment matrix. Cosmic rays also penetrate near-surface sediments. Mineral grains exposed to this radiation progressively acquire the property of releasing light when subsequently heated; this phenomena is termed thermoluminescence.

Electron Trapping by Minerals

As noted by Singhvi and Mejdahl (1984) "a satisfactory model explaining the TL emission of quartz and feldspars is still lacking." Despite this, numerous studies have demonstrated that TL does indeed increase with increasing sediment age (see reviews by Wintle and Huntley, 1982; Singhvi and Mejdahl, 1984). Different minerals also have different sensitivities to radiation; for example feldspar has 10 times the sensitivity of quartz to γ-radiation, but some varieties of feldspar lose 40% of their natural TL after three months of storage at room temperature (Dreimanis et al, 1978, p. 58). Loss of TL resulting from storage between laboratory irradiation and glowing is termed "anomalous fading."

Release of TL by Heating

Sediments heated to 150°-450°C will emit photons which can be measured by photomultiplier tubes. Heating in excess of 500° C will empty all electron traps, so that any subsequent heating will show no TL; such a material (pottery, sediments baked by lava flows) is said to have been "completely zeroed" (Fig. 1a). The original use of TL in dating archaeologic pottery was based on the fact that all the TL present today had been acquired since firing. If it could be determined from the present TL how much radiation the sample had received (the *total dose*), and from the radioactive components what the *yearly dose rate* was, then the TL age of the sample is merely the former divided by the latter.

The fact that natural sediments are never heated to 500°C and are thus never completely "re-zeroed" makes dating of sediments slightly different than with pottery (Fig. 1b). Because some TL will be residual from the silt grain's earlier history (Io), this component must be identified and subtracted from the total TL to yield the TL acquired since deposition (Id).

Summary of Laboratory Procedures

The sealed sample is checked for porosity and moisture content upon receipt and the content of U, Th, and K is measured; procedures are detailed by Wintle and Huntley (1980). Then the outer portion of the sample is discarded and the sample is leached of carbonates and organics. A particular size fraction of the remaining minerals (dominantly quartz and feldspar) is then isolated, usually from 4-11 m (fine silt). All this work must be performed in dim light. Grains are mounted on Al-discs and heated (from 1^{o}-20^{o}/sec) while the amount of luminescence is measured. The resulting graph of temperature versus photons emitted is termed a "glow curve." The amount of TL energy emitted is proportional to the age of the sample since it was last "re-zeroed." This basic strategy underlies all TL dating.

To calculate how much radiation created the TL observable in today's samples, (the total dose), the sample is glowed, the TL is measured, and all electron traps are emptied (Figs. 1a + b). The sample is then re-irradiated with known levels of radiation in the lab and the TL is measured for several known total doses. The total dose of lab radiation which yields the same amount of TL as that observed in the natural sample is termed the "equivalent dose" or ED, and it is presumed to be equal to the total dose which the sample actually received in nature. For sediments the ED is composed of two components, one representing dose acquired before deposition (Do) and another representing dose acquired since deposition (Dd).

Three methods of determining ED and Dd are in common use. The R-β method starts with multiple discs of the same sample, half of which are partially zeroed (or "bleached") by exposure to solar or sunlamp radiation. The TL of one disc of each group is then measured, the one exposed to sunlight being lower because of partial trap emptying (Fig. 2a). Next, one sample each from the natural and bleached groups is irradiated with a known level of radiation, and the total TL of these two samples is measured. This is done for several levels of radiation. The resulting graph of dose versus TL yields two curves. The extrapolated intersection of the two curves shows what total dose should have been necessary to create the observed natural total TL, and how much zeroing by sunlight had occurred prior to deposition (Fig. 2a). A second method employs a long (1000 min) sunlamp bleach to zero the sediment as far as possible, to the residual level. A dose curve is built up as in the previous examples (Fig. 2b), which by extrapolation can yield the ED. The third method, termed regeneration, uses samples that are both bleached by sunlight and then restored by known levels of radiation to release TL. The slope of the regenerated TL growth is assumed to be the same as a natural TL growth curve, so the natural (unbleached) TL is measured, and a line is extrapolated backwards through this point with a slope equivalent to that of the regenerated growth curve. The intersection of this line with zero TL indicates the accumulated dose in the specimen (Fig. 2c).

Because the TL sensitivity of minerals is less for α than for γ or β radiation, glow curves are generated for each type of radiation. Once a consistent ED has been found, sample age is calculated from:

$$\text{age} = \text{ED}/[(\gamma + \beta \text{ dose rate}) + k(\alpha \text{ dose rate})] \qquad (1)$$

where k = the ratio of α to β sensitivity, ranging from 0.05-0.5 (Wintle and Huntley, 1982, p.33)

TL DATING OF SEDIMENTS

Previous Work

TL dating of Quaternary sediments began in the USSR in the early 1960's, but this work was not reviewed in English-language journals until 1978 (Dreimanis et al, 1978). Studies outside eastern Europe began to be reported in the 1970's (e.g. Huntley and Johnson, 1976), and in the last 10 years considerable activity has occurred in the USSR, Europe, China, India, Australia and to a smaller extent in North America. Two excellent reviews by Wintle and Huntley (1982) and Singhvi and Mejdahl (1984) cover current laboratory procedures and TL dates from around the world; Berger (1985) mentions recent Canadian work.

Most TL studies to date have involved loess, because loess is an homogenous sediment and is highly bleached of pre-existing TL by predepositional sun exposure. TL dating of the classic Chinese loess sequences (reviewed by Singhvi and Mejdahl, 1984, p. 22-34) has yielded dates from 8 ka to 250 ka; even older sediments were sampled, but all TL traps had by then been saturated and only minimum ages could be determined. Other sediments dated by TL include dune sands, deep oceanic sediments, glaciofluvial and glaciolacustrine sediments, mudflows, and till (Singhvi and Mejdahl, 1984, p. 22-34). Problems arise if these sediments are only briefly or never exposed to sunlight before deposition, in which case they are not zeroed. In environments with complex erosion/deposition histories such as glacial margins, Quaternary sediments may be a mixture of materials of several ages, some of which have been bleached by sunlight and others which have not. Glacial tills and rapidly deposited glaciolacustrine silts therefore usually yield poor dates (Berger, 1985), while some more slowly-deposited water-laid silts have yielded reliable dates (Singhvi and Mejdahl, 1984, p. 30-33; Berger, 1984).

Sampling

Sampling for TL must take into account the unique properties of the dating method. To avoid bleaching by sunlight, the sample must be taken from a freshly-cleaned cut or core, and protected from sunlight after sampling. In addition, the sample must be as undisturbed as possible, so the natural porosity can be measured. The field moisture content should be preserved by making the sample container airtight. One method the author has employed for vertical exposures is twisting a steel soup can directly into a fresh face. The lip of the can on the open end can be cut with tin snips to create a multi-toothed cutting edge (cuts must be short to avoid weakening the can). When the can has been augured in flush with the face, the material surrounding it is dug away, and the end is quickly trimmed. The can is then sealed with aluminum foil, wrapped in duct tape, and placed in a sealed plastic bag. Samples should be submitted for analysis as soon as possible after collection to avoid moisture loss or penetration by sunlight.

Problems in Interpretation

Complex Moisture History

Water in sediment pores will absorb radiation and thus lower the effective dose rate. Therefore, the average moisture content of the sample during its burial history must be known. For deposits which were deposited subaerially and have remained at or near the surface (such as loess), today's moisture content is probably similar to the average since deposition. Water-laid sediments, however, were originally deposited at saturation moisture contents, but today may be found either far above the water table, near it, or beneath it. In particular lacustrine sediments which are deposited in lowlands and stay near fluctuating water tables are greatly affected by moisture-absorption of radiation. Singhvi and Mejdahl (1984, p. 14) state that, overall, "estimate of the mean water content...is perhaps the single major source of error."

Currently laboratories measure the moisture content at saturation (or porosity) of the sample as received, and assume that the mean water content through time has been either 50% (Singhvi and Mejdahl, 1984, p. 15) or 75% ± 25% (Alpha Analytic, 1985, pers. comm.) of the saturation value. This moisture value is used to correct the dose rate for α, β, and γ radiation (each has a different absorption coefficient), and the corrected dose rate is then divided into the ED to yield the TL age. For lacustrine samples which were deposited at saturation and perhaps saturated for much of their recent history, the 50%-75% estimate may be too low. Therefore, such dates will assume less moisture absorption than actually occurred, will overestimate the dose rate, and the TL date will be younger than the true age. The converse can also occur.

When trying to reconstruct the moisture history of any Quaternary unit, two aspects must be addressed. First, what has the climatic history been since deposition? Higher ratios of precipitation to evapotranspiration occurring in glacial/pluvial times created large perennial lakes, raised groundwater tables and (based on vegetation changes) increased soil moisture levels (Brackenridge, 1978). In contrast, evidence suggests that the Altithermal (or Hypsithermal) period from 8 ka-5 ka was drier than at present (Deevey and Flint, 1957). If the approximate age of the sample is known, its moisture content can be partitioned between wet and dry periods, using the widely-accepted oxygen isotope stages for time control (Morley and Hays, 1981). Secondly, if dealing with water-laid sediments, when did incision and abandonment of the depositional surface occur? As incision progesses, the water table should fall, independently of climatic changes. Techniques of reconstructing moisture histories are described in Rendell (1985) and also by the case history section of this paper.

Compaction History

Quaternary sediments deposited at low bulk densities slowly compact and lose pore space as they are buried to increasing depths. This phenomenon is most pronounced when original densities are low (as in lacustrine or marine sediments and loesses) and less pronounced in denser deposits (such as lodgement tills). Practically, what this means is that porosity (and thus water content at saturation) has been decreasing through time. Therefore, today's porosity is less than the mean porosity through time; this in turn reflects on estimates of the mean moisture content. A graph comparing porosity with time can be constructed assuming an initial porosity and measuring porosities throughout the extent of the stratigraphic section. An example of compaction over 20 ka in marine silty clay (Berger et al, 1984) shows a decrease from saturation water contents of 1.33 at the surface to 0.74 at 3.5 m depth.

Incomplete Bleaching Before Deposition

If silt particles are eroded from an older deposit, and redeposited without sufficient exposure to sunlight, they will retain considerable TL from their prior history (inherited or residual TL). Usually, exposure to sunlight for a few hours reduces previous TL levels by factors of four or five (Singhvi and Mejdahl, 1984, p. 6). Wintle and Huntley (1982) describe numerous cases where material collected from the modern surface has extremely low TL. Even with an intervening layer of water (0-2.6 m deep), a substantial reduction in TL was reported by Kronborg (1983). Storage of feldspar samples at the bottom of a 7 m deep lake for four days caused a 50% reduction in TL. These results imply that not only loess, but also shallow-water-laid sediments may be appreciably zeroed before deposition.

Sediments that are rapidly eroded and redeposited (landslides, debris flows) or that are eroded and redeposited underneath ice (till) may never be exposed to sunlight. Likewise, fluvial sediments that are transported and deposited at night will not be bleached. Jungner (1983) proposed a method to correct for the proportion of grains in a fluvioglacial sand which were deposited at night.

The sunlamp bleaching steps currently used by laboratories can be modified for shallow water-laid sediments by placing various filters over the sunlamp to duplicate the filtering effect of water (Berger 1984, 1985). If this is not done, then water-laid samples submitted for dating may be *over*-bleached by the sunlamp. In this event, the amount of residual TL will be *under*estimated and the resulting TL age will be greater than the true age of the sample. This effect becomes less important for older samples, because any residual TL becomes a smaller percent of the total TL. As a rule , the submitter should inform the laboratory about the depositional environment of each sample so proper bleaching can be performed.

Trap Saturation

Mineral grains have a limited ability to store TL energy. Once all the electron traps have been filled to capacity the TL of the sediment reaches a maximum, and only a minimum age can be estimated. Traps can be "saturated" by either very long exposures or very high dose rates. In addition, quartz has less trap depth than feldspars, so at a given dose rate and exposure time quartz will saturate first. At typical dose rates, pure quartz sediments will reach saturation by 10-70 ka (Wintle, 1982; Berger, 1985); the higher the feldspar content, the longer before saturation occurs. In case histories reviewed by Singhvi and Mejdahl (1984), saturation was reported for polymineralic sediments older than roughly 250 ka. If the U or Th content of the sediment is abnormally high, then saturation will be reached much sooner.

Complex Radiation History

Uranium is soluble and mobile in groundwater as UO_2^{+2} so uranium-laden groundwaters may add an additional radiation component to sediments. For sediments which were once saturated with radioactive groundwater but now are above the water table, the presence of such an occurrence would be hard to detect. If the uranium-bearing groundwater had small concentrations of U and produced no precipitates in the sediment, then there is no geological evidence preserved today of past (higher) radiation levels. Conversely, if the sediment was dry for most of its burial history, and was only recently invaded by uranium-bearing groundwaters, today's dose rate may be higher than the long-time average (J. Stipp, 1985, pers. comm.). Thus the history of mobile radioactive components in groundwater is tied into the reconstruction of water table history, which was previously described. One direct trace the groundwater may leave is calcite or silica cement with a small U or Th content; these contents can be used to approximate the U/Th content of the groundwater.

Other Sources of Error

Some sources of error over which the sample submitter has little control are: 1) anomalous fading in feldspars, 2) nonlinearity in lab-generated TL growth curves, 3) radon loss during α-counting of dry powders, 4) glow curve peak shifts manifesting non-first-order kinetics behavior, and 5) changes in sensitivity to subsequent doses, induced by sunlamp exposures. Techniques to minimize errors caused by these factors are presented by Berger (1984), Lamothe (1984), and Berger (1985), and will not be discussed here.

If the sample submitter can adequately describe the depositional processes and moisture history of the sample, and the lab can minimize the errors described above, then an accurate age should be obtained.

CASE HISTORY: BONNEVILLE BASIN, UTAH

Overview of the Investigation

A neotectonic study of the Hansel Valley area in north-central Utah (Fig. 3) was conducted to determine the degree and timing of late Quaternary earthquake activity. The area was chosen because it was the site of Utah's largest historic earthquake (M 6.6, March 12, 1934) which created a fault scarp 50 cm high (Walter, 1934). The area has also been a focus of intense seismic activity, recording 19 earthquakes with epicentral intensities of IV or greater since 1850 (Arabasz et al, 1979). Dating fault movement required dating the Lake Bonneville shore zone and lake bottom sediments disrupted by faulting and liquefaction.

Fault Features

The 1934 fault scarp on the southwestern side of Hansel Valley extends northward into a pre-historic scarp up to 9 m high (Fig. 3; Robison and McCalpin, 1985). Fortuitously, a 10-15 m deep arroyo (West Gully) crosses the trend of this fault zone and exposes a complexly faulted sequence of lacustrine and alluvial sediments. Detailed logging of arroyo walls revealed nine stratigraphic units, some of which were faulted or deformed by earthquake shaking. Although the relative sequence of deposition and faulting can be deduced from cross-cutting relations (see Fig. 4), the absolute age of faulting could only be determined by dating the strata. The only material found for radiocarbon dating (gastropod shells) was restricted to a single unfaulted unit, so this would not provide adequate age control for the entire sequence of deposition and faulting. As a result, five TL dates were performed, one of which was controlled by radiocarbon and amino acid dates on shells from the same location.

Stratigraphy in the West Gully

A composite stratigraphic section from the West Gully is shown in Fig. 5. For each unit, the position within the stratigraphic section and sedimentological characteristics provide a first approximation for age. The uppermost six units are clearly lacustrine, ranging from well laminated silts and clays (units 5 through 9) of lake bottom origin to a basal transgressive beach gravel (unit 4). Presuming that this sequence represents the latest (Bonneville) lake cycle, the lake-level curves of Scott et al (1983, Fig. 5) or Currey et al (1984) indicate ages from 35 ka to 12 ka. Lying uncomformably beneath this sequence are two massive silt units, separated by an unconformity marked by desiccation cracks and gypsum crystals. The sedimentology and ostracod assemblages suggest that these are marsh deposits which locally overlie shoreline gravels of pre-Bonneville age. Because no deep-water facies deposits are present, it is inferred that units 2 and 3 in Fig. 5 were deposited on the margins of a shallow lake; the correlation and age of such a lake was unknown.

Lying unconformably beneath the silts are well-laminated dense, intensely fractured silt and clay beds of deep lake origin (Fig. 5). Although no weathering profile was observed at the top of these deposits, they are inferred to be equivalent to the Little Valley lake cycle described by Scott et al (1983) which are 90-150 ka old. An alternative explanation was that units 2 and 3 represented the Little Valley cycle, and unit 1 was even older, representing a mid-Pleistocene lake cycle of unknown age. Because each package of units (1; 2 and 3; 4 through 9) had undergone progressively more faulting with age, TL dating was performed in hope of distinguishing between the two alternative hypotheses.

TL Dates

TL dates originally reported by Alpha Analytic Inc. confirmed that units 4 thorugh 9 were of Bonneville age, and suggested that Unit 1 was of Little Valley age (Table 1; also includes data of McCoy (unpub.) from Promontory Point, UT). Units 2 and 3 had initial TL ages of 65.9 and 67 ka respectively, suggesting they were deposited during oxygen isotope stage 4 (58-72 ka; Morley and Hays, 1981). The existence of a shallow lake of this age which did not rise above about 1340 m had recently been proposed by Oviatt et al (1985).

The initial TL dates were computed based on today's water contents. To calculate the mean water content through time, it was necessary to determine: 1) the porosity through time, and 2) the percent saturation through time. The compaction history was estimated from the decreasing water contents at saturation in today's samples (Fig. 6). The saturation history was estimated assuming that samples were saturated during even-numbered oxygen isotope stages and unsaturated during odd-numbered stages, to the same percent of available porosity as that existing today. For each sample, the mean water content through time was calculated as the weighted average of periods in which the available porosity was saturated, together with periods in which it was unsaturated (typically 35% of saturation; Fig. 6).

The mean water contents were then used to recalculate TL ages on a TL age versus moisture content graph (Fig. 7). Corrected TL ages were 11%-22% greater than those based on today's water contents, reflecting the importance of long saturation at higher porosities in the sample's past. Four of the five dates can be correlated with the broad outlines of Quaternary climatic history. Unit 1 (138 ka) dates as late isotope stage 6, reflecting late deposition in the deep Little Valley lake. Units 2 and 3 (76 and 82 ka) actually fall in late stage 5 (5a), but climate curves (Aharon, 1983) show that cooling which reached a maximum in stage 4 had already begun by 82 ka. These sediments are therefore interpreted as marsh deposits formed as stage 4 lake waters rose and began to impede marginal drainage. The thin lake sediments which were probably deposited at this location were presumably removed by erosion during stage 3 (58-27 ka). Unit 6 yielded a ^{14}C date on shells of 15.5 ka and an amino acid date of 21 ka, confirming the Bonneville age inferred from sedimentology. However, the TL date of 48 ka is much older. Because this unit is a highly deformed silt with roll structures, diapirs, convoluted bedding, and "floating" pebbles, it is inferred to have resulted from either submarine slumping or earthquake-induced liquefaction of bottom sediments. Either mechanism could have mechanically mixed the Bonneville bottom sediments (25-15 ka) with the older underlying stage 4 sediments (75-80 ka); a 50/50 mixture would yield an apparent TL age of 45-52.5 ka. TL growth curves from the R-β technique showed that the sample had high residual TL, which supports this explanation. Unit 8 (13 ka) represents deposition in the waning stages of the Bonneville cycle according to the lake level chronology of Scott et al (1983, Fig. 5); this is consistent with its position near the top of the stratigraphic section.

In summary, TL dates are consistent with physical stratigraphy, sedimentology, and paleoecology, and reveal three lacustrine cycles, one of which had not previously been dated (stage 4). Their ages allow limits to be placed on recurrence intervals for surface faulting, as described below.

Late Quaternary Fault History

Cross-cutting relations and liquefied layers in the West Gully section reveal a history of recurrent faulting over the past 150 ka. The basal clays are extensively fractured with conjugate shears spaced as closely as 1 cm in fault zones. In most places the Bonneville transgression clearly truncates these small-displacement fractures, but in one place (between 44 and 45 m W on Fig. 4) transgressive gravels are laid into an open tension fissure atop earlier fill, suggesting faulting not too earlier than 27 ka. Bonneville gravels are offset along pre-existing faults by up to 2.7 m, but these faults are truncated by an early Holocene fluvial deposit (unit 10, Fig. 4). Later faulting is therefore bracketed as between roughly 27 ka and 10 ka.

The two convoluted silt units (Figs. 4 and 5) could both have resulted from earthquake shaking, or alternatively, one could have resulted from turbidites following the Bonneville Flood. Faults can be traced through unit 6 (2-3 m W, Fig. 4) implying that at least one fault event post-dates that unit (i.e. is younger than 15-21 ka). The upper convoluted silt appears to be part of a large lateral spread, which may also be responsible for the disappearance of the fault scarp in this area (see Fig. 3). Independent geomorphic evidence suggests the fault scarp was formed between 12 and 15 ka; the uppermost convoluted beds of unit 8 have a TL date of 13 ka. Because the age of the lower convoluted silt (unit 6) is earlier than that of the Bonneville flood, it too may represent earthquake liquefaction, although at deeper water depths and higher pore pressure than in unit 8.

In summary, evidence exists for multiple surface-faulting events occurring between roughly 138 ka and 27 ka (with the last event not much prior to 27 ka), possibly one event between 21 ka and 15 ka, another at around 13 ka, and a M 6.6 in 1934 A.D. Some individual traces had a long history of movement (32-47 m W, Fig. 4) whereas others moved in Bonneville time only after quiescence extending at least as far back as 82 ka (35-45 m, E, Fig. 4). Net offset across the entire deformation zone was 1.3 m down to the west, similar to the surface offset of fault scarps both north and south. For a more detailed discussion of magnitude and recurrence, the reader is referred to McCalpin (1985) and McCalpin et al (in prep.).

CONCLUSIONS

TL dating served to place closer limits on times of faulting of lake beds in the last 138 ka than would have been possible with other methods. Although samples are easy to collect and dating is relatively inexpensive ($360 versus $500 for an accelerator ^{14}C date), the lab dates must be based on numerous assumptions, such as the extent of pre-depositional bleaching (in part corrected for by the R-β method) and the water content history (worked out by the sample submitter). Even without such corrections, however, TL dating can provide order-of-magnitude dates for non-carbonaceous, silty lacustrine sediments which can at a minimum assign them to the correct oxygen isotope stage.

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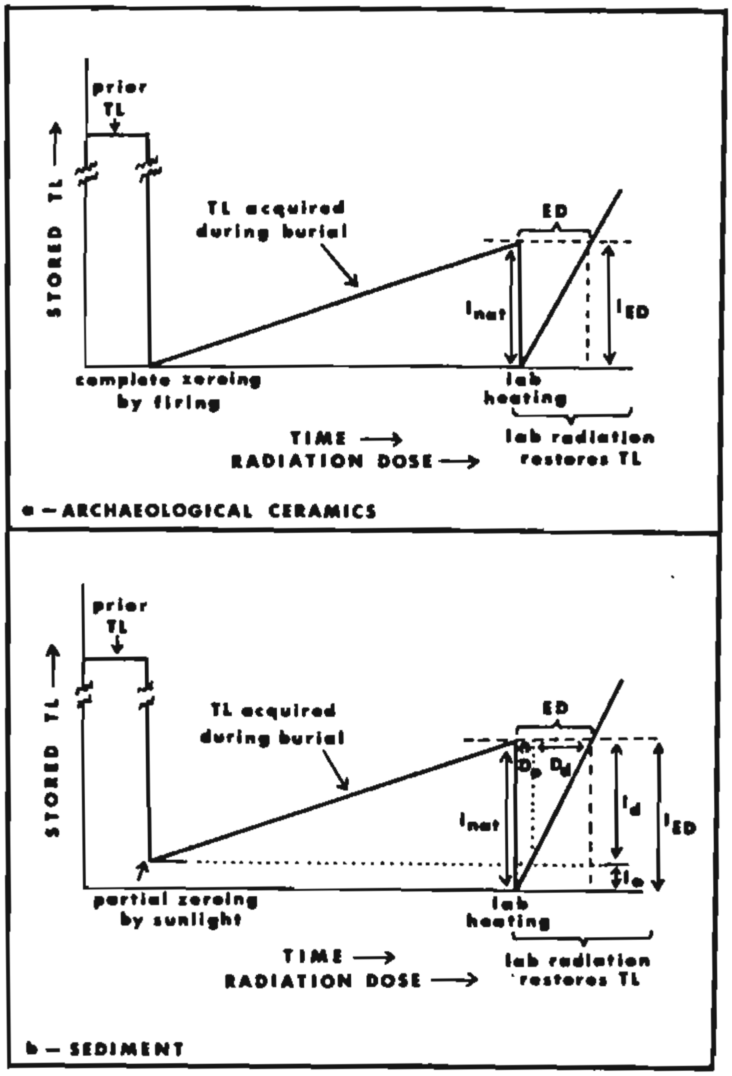


Fig. 1

Schematic diagrams of TL acquisition with time.
a. Archaeological ceramics are completely "zeroed" by firing in excess of 500° C. Lab heating releases acquired TL, and then restores TL until the natural level is again attained. The equivalent dose (ED) is that dose of lab irradiation which is needed to mimic the natural TL.

b. A similar procedure, but sediments are only partially "zeroed" by sunlight. Therefore, the resulting ED actually represents two components; that dose acquired since deposition (Dd) and that dose inherited from previous geologic history (Do). Dd is used to compute sediment age. Modified from Singhvi and Mejdahl, 1984, Fig. 1.

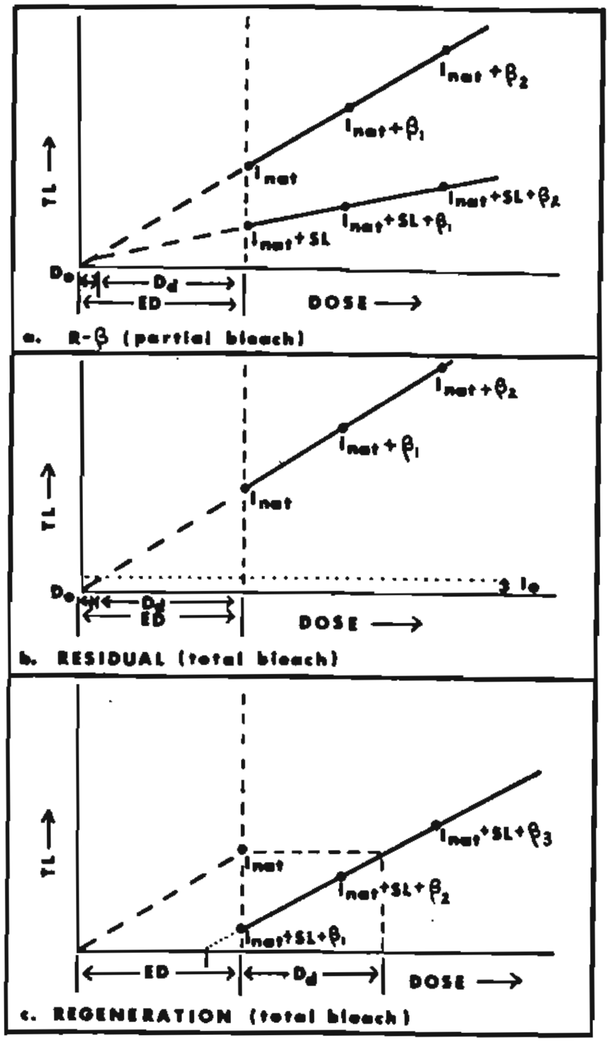


Fig. 2

Three methods used to determine ED and Dd.
a. The R-β method utilizes short sunlamp exposures at several levels (only one is shown) with lab irradiation to extrapolate backwards to ED and Dd. Non-linear curves often introduce sources of error.
b. The residual method uses a long (total) sunlamp bleach with lab irradiation to extrapolate ED and Dd; it presumes the sample had $I_0=0$.
c. The regeneration method assumes the slope of the bleached plus irradiated curve (SL + β_n) is the same as an unbleached curve (passing through I nat). Again, total bleaching is presumed in the sample. Modified from Singhvi and Mejdahl, 1984, Fig. 4.

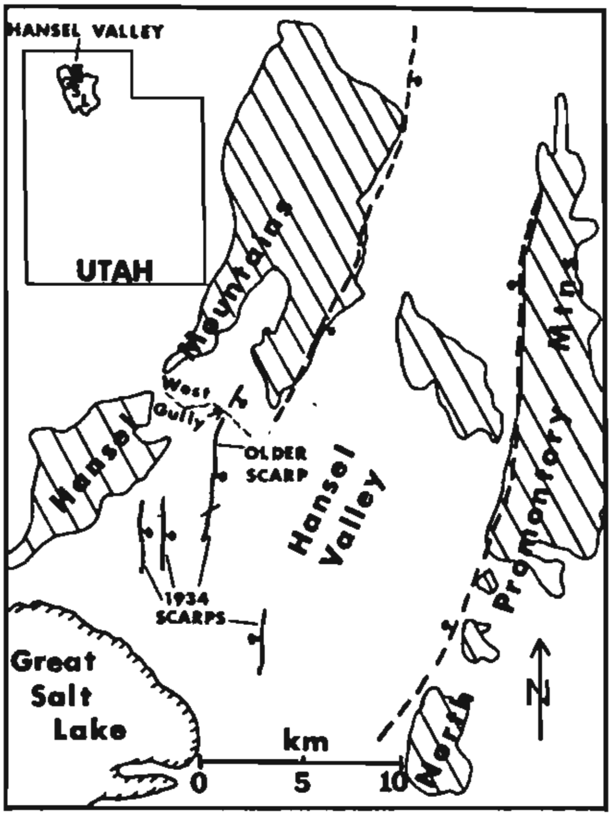


Fig. 3

Location map of Hansel Valley, north-central UT. The Hansel Valley graben is bounded by inferred normal faults (heavy dashed lines) on the east and west. The 1934 scarps and older Quaternary scarp are shown by heavy solid lines. TL samples were collected in the West Gully between fault scarp traces.

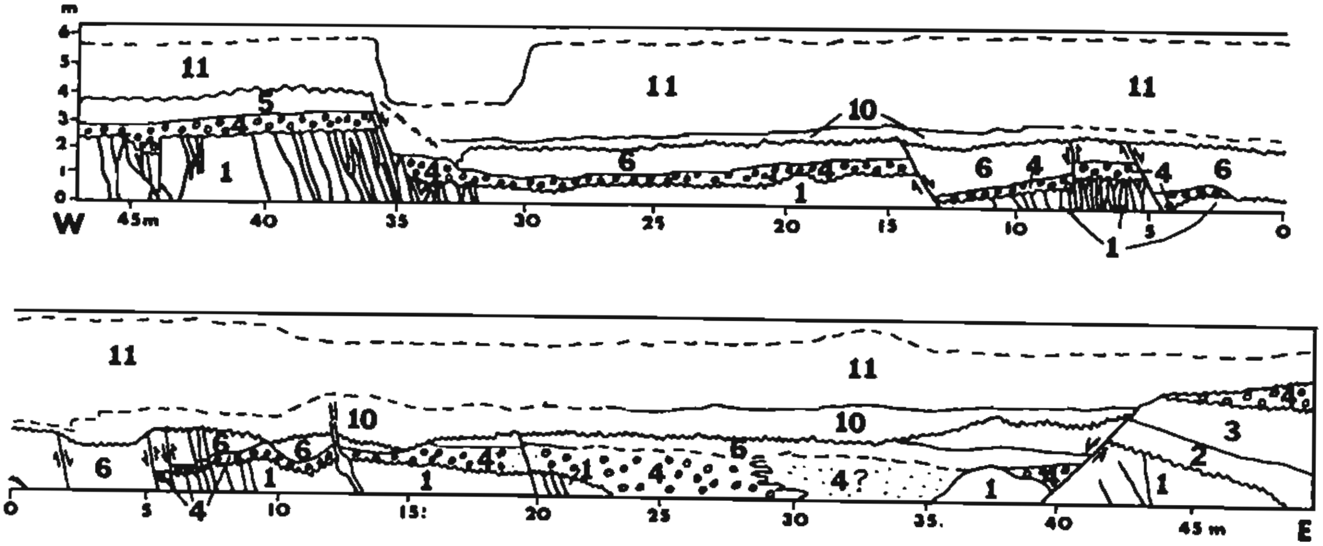
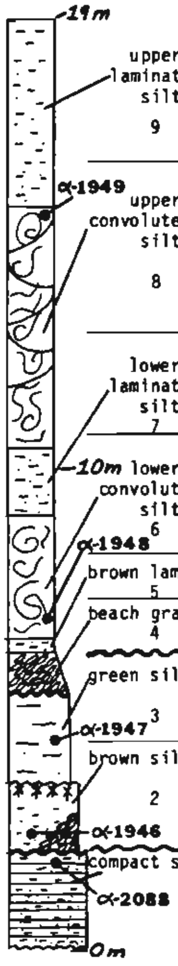


Fig. 4

Partial log of the north wall of the West Gully between traces of the Quaternary fault scarp. Faults and fractures (heavy solid lines) are mainly restricted to unit 1 below unconformities beneath units 2 or 4. In some places, the unit 4 unconformity (Bonneville transgression) is faulted by up to 2.5 (35 m W; 42 m E). Unit numbers refer to composite stratigraphic section in Fig. 5.



STRATIGRAPHIC UNITS	SEDIMENTOLOGY & Deformation	OSTRACODS (by Rick Forester) Species	Inferred Environment	ABSOLUTE AGES (yr B.P.) ^{14}C	amino acids	TL	LAKE BONNEVILLE CHRONOLOGY	Oxygen Isotope Stage
upper laminated silt 9	well laminated silt & clay	mixture of species	mixed alkaline poor & alkaline rich waters; lake regressing				Bonneville cycle-regression from Provo shoreline	1
upper convoluted silt 8	intact, rotated blocks of well laminated silt & clay, similar to unit above					13,000 (not fully zeroed)	-drop to Provo shoreline? -Bonneville flood?	2
lower laminated silt 7	alternating silt & clay laminae with 5 cm thick, rippled med-cse sand beds	"profundal assemblege"	alkaline rich water-deep lake				Bonneville cycle highstand	2
lower convoluted silt 6	intensely convoluted mixture of clay, silt, sand, & floating pebbles; roll structures common			*15,450 + 650 (min.date)	*21,000 prelim	(not fully zeroed) Too old 48,000	deepening water	2
brown lam.silt 5	well laminated silt		alkaline poor water, low-stand lake lake level rising					2
beach gravel 4	cross-bedded, well sorted medium pebble gravel						Bonneville cycle transgression	2
	MAJOR UNCONFORMITY							
green silt 3	green silt with some clay, poorly laminated		alkaline poor water, low-stand lake			82,000 (best date)	"Alpine" (early Wisconsin) cycle	4
brown silt 2	brown massive silt, gypsum crystals at top, laminations better defined toward bottom; locally overlies lacustrine bar gravels	Heterocypris n.sp. C. rawsonii L.staplini I. bradyii	alkaline poor water marginal lacustrine groundwater environment			(some trap saturation) 76,000		4
			MAJOR UNCONFORMITY					
compact silt	well laminated silt & clay, very compact; intensely fractured w/ steeply dipping small displacement joints	C.Sp. caudata type L. Sappaersis L. ceriotuberosa L. staplini C. beacorensis	alkaline rich water, deep lake			138,000	Little Valley Cycle	6 ?

Fig. 5

Composite stratigraphic section from the West Gully. Evidence from sedimentology and ostracod assemblages (interpreted by R. Forester, USGS) is compatible with TL, ^{14}C, and amino-acid dates.

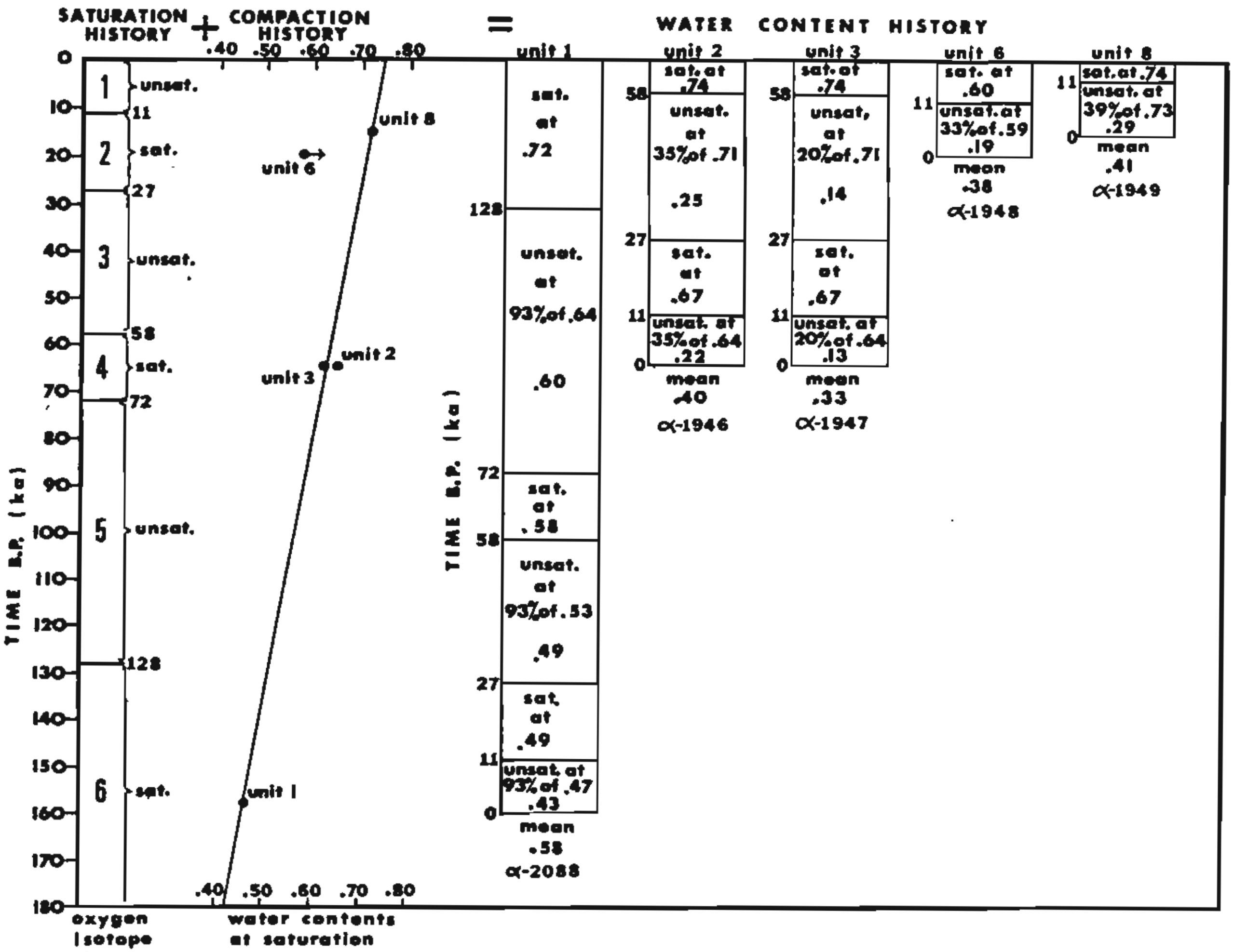


Fig. 6.

Water content histories of TL samples calculated from saturation history and compaction history. 1) Units were assumed to be saturated during glacial/pluvial stages (even numbered stages) and unsaturated in inter-glacials (odd-numbered stages). 2) Available capacity for saturation through time was assumed to follow the observed decrease in saturation water contents with observed age, due to compaction. 3) Water contents for each oxygen isotope stage were computed by multiplying the percent of saturation times the available pore space. Values used for unit 6 reflect lower porosities due to vibratory compaction during contemporaneous earthquakes.

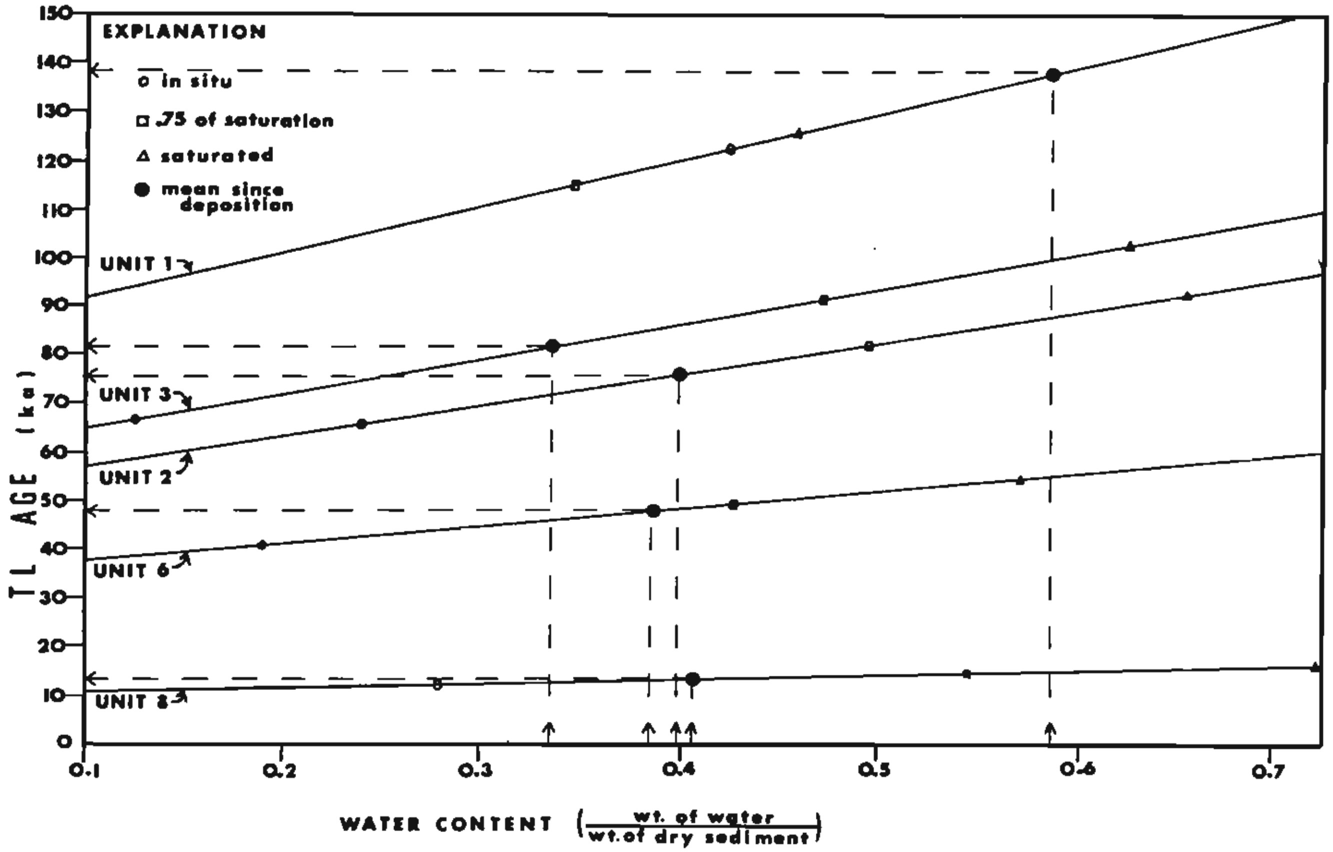


Fig. 7

Graph showing the effect of water content on apparent TL age. Mean water contents calculated from Fig. 6 yield TL ages which are 11-22% greater than TL ages originally reported based on in-situ water contents. The effect of changes in water content on TL age is generally more pronounced for older samples.

Table 1

SUMMARY OF LAKE BONNEVILLE TL DATA

SAMPLE number[1]		α-924	α-921	α-922	α-2088	α-1946	α-1947	α-1948	α-1949
submitter and date		------McCoy, 1984-----------			----------McCalpin, 1985--------------------------------				
stratigraphic unit[2]		Pokes Pt.	Little Valley	Bonneville	Little Valley	"Alpine"	"Alpine"	Bonneville	Bonneville
Radioactive	U (ppm)	3.6	2.5	5.2	3.1	3.1	3.8	3.0	3.0
Components	Th (ppm)	11.3	8.0	7.8	5.1	8.8	5.5	4.0	7.5
	K_2O (wt%)	1.7	1.9	1.2	1.6	2.4	1.8	1.3	1.7
Water content[3]	in situ	--	--	--	.428	.229	.123	.189	.278
	if saturated	.48	?	.46	.462	.656	.625	.566	.722
relative % of saturation in situ		--	--	--	.93	.35	.20	.33	.39
Porosity[4]		.560	?	.550	.551	.635	.624	.600	.657
Dose Rate[5] (rad/year)		.36[6]	.27[6]	.32[6]	.270	.369	.416	.347	.348
Equivalent Dose (krad)		17.71[7]	14.63[7]	5.74[8]	31.17[9]	24.39[9]	27.94[9]	10.77[10]	3.86[10]
TL age (ka)		>55[a]	65±10[a]	21±3[a]	115.2±17.5[b]	65.9±4.2[b]	67.0±3.8	40.1±3.2[b]	11.7±1.1[b]
					138[c]	76[c]	82[c]	48[c]	13[c]

[1] Alpha Analytic sample number, Coral Gables, FL

[2] Stratigraphic usage according to Scott et al (1983) and McCoy (1981)

[3] Water content = weight of water/weight of dry sediment

[4] Porosity calculated from saturated water content values, assuming density of water = 1.0 g/cm^3 and density of mineral grains = 2.65 g/cm^3

[5] The effective combined dose rate of α, β, and γ radiation at the in situ water content.

[6] Dose rate for moisture content = 50% of saturation value.

[7] Using Regen technique only

[8] Using average of R-β and Residual techniques

[9] Using average of R-β, Residual, and Regen techniques

[10] Using R-β technique only

[a] Assuming water content = 50% of saturation value

[b] Assuming water content = in situ value

[c] Calculating mean water content from compaction and saturation history (see this paper)