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Investigation of the Sediment Movement along the Tenryu–Enshunada Fluvial System Based on Feldspar Thermoluminescence Properties

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ABSTRACT

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The thermoluminescence (TL) properties of feldspar were used to investigate the sediment movement processes in a fluvial–coastal system. Field samples were collected at various locations along the Tenryu River and the Enshunada Coast in Japan. After a series of pretests, an appropriate TL measuring sequence was proposed for this study. Applying this approach, the natural TL intensity of feldspar grains was measured. Owing to the young age of the research area, it was assumed that the natural TL difference was ascribed to the sample depositional environment under which different possibilities of sunlight exposure exist. Surface sediment particles in the target area were classified into three groups in terms of TL intensities, *i.e.,* river sand with large TL signals, coastal sand with medium TL signals, and dune sand with small TL signals. Stratified configuration of the Nakatajima Coastal Dune was observed from the underground-sample TL glow curves with a top, windblown, dune-sand layer; a bottom, wave-induced, coastal sand layer; and a mixing layer in between. A rather complex sediment-movement pattern in front of the Tenryu River mouth was revealed after investigation of the underwater samples. Because of the seawater influence, acting as an ultraviolet filter to sunlight, underwater samples present a larger, high-temperature TL peak than the low-temperature peak; whereas these two are almost the same for ground samples.

ADDITIONAL INDEX WORDS: *River, coast, dune, surface sand, underground sediment, underwater sample.*

INTRODUCTION

Accurate and reliable measurements of sediment transport are necessary for both developing efficient countermeasures to coastal-erosion problems and proposing better predictive tools in coastal-engineering applications. In a case study of the nearshore sediment processes, identification of sediment sources, sinks, transport paths, and historical evolution are of crucial importance. Therefore, a comprehensive insight is required of the entire fluvial system, composed of both a river watershed (sediment source) and coastal sediment cells (sediment sink) in the nearshore area.

Traditionally, early field works, mainly using fluorescent tracers to investigate the nearshore sediment movement, have involved a variety of techniques. White and Inman (1989) studied longshore sediment transport using dye-marked tracer sands. Net sediment movement over periods ranging from one to five tidal cycles was investigated using fluorescent tracers in Voulgaris *et al.* (1998). Later, McComb and Black (2005) used two colors of artificial fluorescent tracers to monitor the sediment entrapment/bypassing of a port entrance as well as the sand movement from a nearshore dredged-sand dump mound. However, sand tracer studies suffer from many practical problems in sampling the tracer distribution and in elaborate methods of determining tracer concentration in samples, *e.g.,* counting. Nevertheless, the artificially injected sand tracers are different from the natural subaqueous bedload in physical and chemical properties, *e.g.,* grain size, sand size distribution, shape, specific density, and mineral components, which may introduce inaccurate or unreliable field measurements. At the same time, other methods for investigating sediment movement in the field were introduced, such as traps (Dean, 1989), mineral composition analysis (Sato *et al.,* 2004), and magnetism analysis (Liu *et al.,* 2007). Among those methods, using large-scale sediment traps, such as inlets or groins, is a rather passive approach, in which transported sediment is accumulated for periods of days to years. Mineral or magnetism analysis is strongly related to the local geology, and in general, such techniques are fairly laborious. Intercomparison among various methods for study of coastal sediment transport, including each technique's theory, problems/solutions, advantages/limitations, and practical tricks was summarized and presented in White (1998).

Recently, Rink (1999, 2003) suggested the use of the thermoluminescence (TL) properties of quartz and feldspar grains as a transport indicator in the study of various coastal de-

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positional processes. Shirai and Omura (2007) and Shirai, Tsukamoto, and Kondo (2008) proposed the use of the percentage of sand particle bleaching to investigate the sediment movement process, based on the optically stimulated luminescence approach. In these methods, in contrast to the traditional injected-tracer methods in which an artificial material is added at a particular moment, the sediment particle constituting the investigated object (natural sand), itself, is used as a tracer to monitor the sand movement. This would allow more facility and reliability in experimental design of coastal process studies. Investigations of the longshore and cross-shore sediment movement, and the tracing of coastal sands sourced in areas of river deltas, local coastal sequences, and anthropogenic deposits, are all potential applications for this new technique. Pioneering studies have been conducted on storm deposits along a specified cross-shore beach profile in Canada (Rink, 1999) and on the littoral sediment movement along the Israel coast (Rink, 2003). Only surface samples were considered in these studies. However, more studies are needed to establish the degree of TL homogeneity and heterogeneity within surface, underground, and underwater sand bodies. Further research and field applications are needed to verify the feasibility and applicability of the TL property as a useful tool for studying nearshore sediment movement.

In this article, we applied feldspar TL measurements to an investigation of the sediment transport along the Tenryu–Enshunada fluvial system. The regional sand transport and historical evolution of the alluvial deposits in the corresponding area were investigated by considering TL signal differences among collected samples to outline characteristics of the sediment movement in the fluvial system. After a series of pretests, an appropriate TL measurement sequence was proposed for this study. Applying this approach, the grain's natural TL signals were measured for the collected field samples. Intercomparison and discussions of the measured, normalized, natural TL signals, together with comparison between a natural and a test dose of the TL integration over a temperature range of 200°–400°C display a comprehensive feature regarding the spatiotemporal distribution of sediment movement in the target area.

THERMOLUMINESCENCE

Quartz and feldspar grains exhibit laboratory-stimulated luminescence as a consequence of their natural radiation exposure while buried in a sediment environment. Nuclear radiation is emitted when a nucleus undergoes radioactive decay. Such natural radiation is mainly from potassium (^{40}K), thorium (^{232}Th), uranium (^{238}U), and their daughter products (there are also certain contributions from cosmic rays, as well as a minor contribution from rubidium, ^{87}Ru), which induces the electron ionization in the grain crystal lattice. Then, the ionized (detached) electrons are diffused and trapped in the lattice defects (Aitken, 1998). This irradiation and storage process is presented in Figure 1a, through an energy-level diagram. Luminescence is the emission of light from the particle crystal after being stimulated by certain external energies through the detrapping agency, such as heating or absorption of a photon of light. The former is termed thermoluminescence (TL), and the latter is known as optically stimulated luminescence (OSL). The light emission occurs during the detrapping–recombination of electrons between traps (donors) and luminescence centers (acceptors) in the defect structure of the quartz or feldspar crystal lattice. This electron eviction and light emission mechanism is illustrated in Figure 1b.

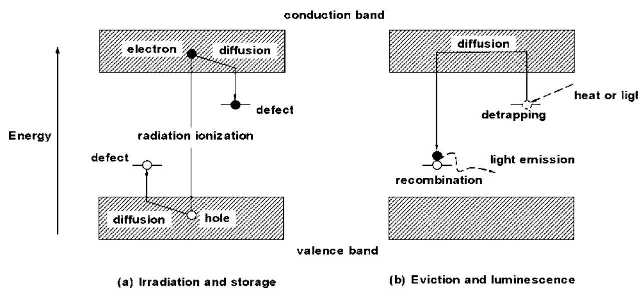

Figure 1. Energy-level diagram for TL and OSL processes (modified after Aitken, 1998).

The magnitude of the luminescence emission in a grain is proportional to the number of trapped electrons and hence to the accumulated energy that has been stored from the flux of nuclear radiation. The more prolonged the exposure to nuclear radiation, *i.e.,* the longer the burial time, the greater the number of trapped electrons. In general, natural erosion and transportation of sedimentary particles from the upstream river watershed to the downstream area, to the river mouth, and finally, to the nearshore region, are accompanied by solar radiation exposure. Such sand movement reduces the particle luminescence signals by depopulating the trapped electronic charges from the lattice defects where they were stored during burial. Considering the extent of the incoming light flux, it is thought that the more significant the light exposure, the smaller the luminescence signal. This illustrates the possible use of TL/OSL as a tool for describing the temporal and spatial sediment-movement processes.

Nevertheless, the same sunlight exposure induces different amounts of reduction (bleaching) of the TL and OSL intensities because of the different sets of donor–acceptor systems (Aitken, 1998; Duller, 1997; Godfrey-Smith, Huntley, and Chen, 1998). Donor–acceptor systems for TL have long response time to light exposure (hours to days), whereas the OSL system is much more sensitive, in terms of response time, on a scale of seconds to minutes. Rink (1999) found no OSL signal remained in the storm-induced samples collected at the subaqueous, swash, berm, and dune areas, whereas there existed a significant difference with respect to the TL signals after measuring the same samples. At the same time, the sample collection requirements are much less stringent in the case of the TL study. In contrast to OSL, in which extreme caution must be used to prevent light exposure during sample collection, using TL allows a minimal amount of additional exposure in the field. Taking these items into account, the present study applied the TL technique for further

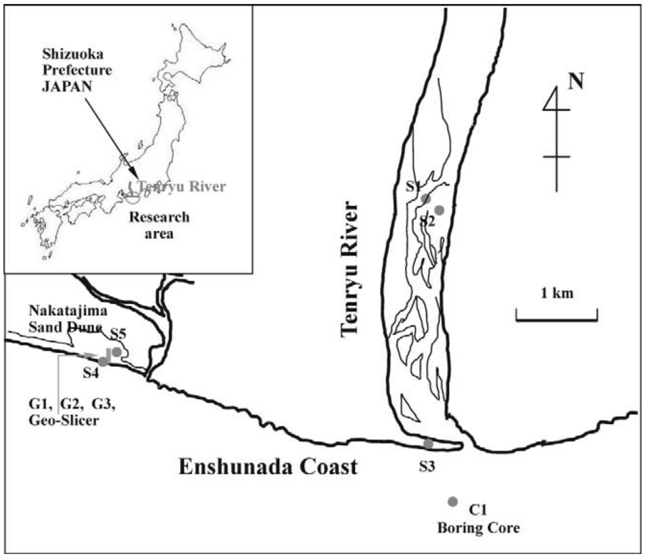

Figure 2. Research area and sampling locations. The ● mark represents the sampling location, and the | symbol represents the geo-slicer survey line along which underground samples G1, G2, and G3 were extracted.

investigation of sediment movement in the case study fluvial system.

RESEARCH AREA AND SEDIMENT SAMPLING

In this study, the target area is a fluvial system composed of the Tenryu River watershed and the Enshunada Coast, which is located to the west of the Shizuoka Prefecture in Japan (Figure 2). There are several typical characteristics related to this region, such as the largest amount of sediment discharge in Japan from the Tenryu River, the anthropogenic impacts from dam construction, sand exploitation, and so on. Coastal sands within this area predominantly originate within the Tenryu River watershed. A couple of hundred years ago, the large amount of sediment discharge from the Tenryu River caused the shoreline of the corresponding area to progress seaward. However, during the economic development of the past several decades, a series of dams was constructed along the Tenryu River, which along with sand dredging, have significantly reduced the sediment discharge to the Enshunada Coast. This causes severe erosion problem along the Enshunada Coast. Based on topographical survey data, it was found that, just in front of the Tenryu River mouth, the present seabed bathymetry, with a 10 m water depth, was only 5 m deep about 20 years ago. After analysis of a series of historical maps, Hiramatsu *et al.* (2008) concluded that the Nakatajima Coastal Dune developed in the past 200 years. Therefore, the present research area is considered to be a rather dynamic region, with a relatively young age from the geological viewpoint.

Sampling locations are also marked in Figure 2. To clarify the spatial distribution of TL signals, *i.e.,* the development of sediment transport processes, surface samples (about 10 cm below the surface) were collected at the subaerial–subaqueous areas, which include two nearby samples extracted at Kaketsuka, S1/S2 (about 3 km upstream from the Tenryu River mouth); one sample from the swash zone at the Tenryu River mouth sand spit, S3; and one sample from the swash zone of Nakatajima Coast, S4 (about 4 km west of the river mouth). Sample S1 was collected from one side of the low-water river channel bank, and sample S2 was from a river sand dune in the high-water channel. In the field, these locations emerge and submerge intermittently, owing to the changes in river water levels (S1/S2) or influences by tide levels and wave climates (S3/S4). Furthermore, surface sands were also sampled at the inland of Nakatajima Coastal Dune, S5. This location is an aeolian environment. Hence, the surface sand at S5 is windblown, with a high probability of being exposed to sunlight. To sample surface sands, an opaque, polyvinyl chloride tube that was open at one end was used. After digging a sampling hole, the tube was inserted into the sand, then, taken out, and immediately put into a dark bag to avoid further light exposure.

To specify the vertical structure as well as the provenance of the Nakatajima Coastal Dune, underground TL samples at different depths were collected along the extracted sand cores in a geo-slicer study, which included three different locations (G1, G2, and G3). G1 and G2 are located along the dune ramp, and G3 is at an interdune area. Details of the geo-slicer study can be found in Takagawa *et al.* (2008). Furthermore, an underwater sample (C1) was collected as a 10-m-long boring core, which was extracted at an offshore point just in front of the Tenryu River mouth at a water depth of 10 m. Sample C1 was used to reveal the sediment moving pattern in a rather dynamic nearshore zone with frequent changes in the bottom bathymetry. During the geo-slicer and boring-core sample collections (the G series and C1 samples), the whole sediment core was covered by an opaque shelter at the beginning, and photographic, dark film cases were used to extract the TL samples at various designated depths. As a whole, great effort was taken to prevent significant, natural light exposure during field samplings.

SAMPLE PREPARATION AND EXPERIMENTAL METHODOLOGY

Sample Preparation

After field collection, all sample pretreatments were conducted in a dark room. In the laboratory, it was of crucial importance that all pretreatment processes were done in semidarkness to avoid the severe risk of underestimating the luminescence signals (Aitken, 1998). Taking into account that luminescence signals are less sensitive to low energy photons (red to green) than to higher energy ones (blue to ultraviolet), laboratory preparation was carried out under subdued, orange light (600 nm), which had little influence on the TL signals. Initially, the collected samples were wet-sieved to obtain the 180–300 μm grain fraction. Subsequently, that fraction was treated with 15% hydrogen peroxide and 18% hydrochloric acid to remove organic matter and carbonate minerals, respectively. Then, the potassium-feldspar–rich fraction (K-feldspar; density less than 2.58 g/cm^3) was isolated by lithium–heteropolytungstate heavy liquid using a separating funnel. All drying was at the room temperature to avoid effects from thermal transfer. Using this approach, following Huntley and Baril (1997), the resulting grains were typically half K-feldspar and half quartz and plagioclase feldspar.

There are many practical advantages of using feldspar in luminescence applications (Duller, 1997; Huntley and Lamothe, 2001), such as the great luminescence intensity of the K-feldspar (suitable for young samples), the significant proportion of potassium, and the avoidance of using concentrated hydrofluoric acid etching. Taking into account that the collected samples in this study were geologically young, the K-feldspar fraction of each sample was used.

Nevertheless, when using feldspars, the difficulty of anomalous fading (Wintle, 1973) has to be considered because, if present, it will introduce an age shortfall into the dating of samples, despite apparently adequate preheating of samples before measurement. Widely discussed mechanisms for anomalous fading include the localized transition model and quantum mechanical tunneling (Aitken, 1998; Duller, 1997). Visocekas *et al.* (1994) proved that the quantum mechanical tunneling was responsible for anomalous fading in feldspars after detecting the tunnel afterglow. They concluded that most feldspars show anomalous fading. Mejdahl (1983), however, showed that many feldspars extracted from sediments and archaeological samples did not show a significant degree of anomalous fading. Later, Huntley and Lamothe (2001) argued that this phenomenon appears to be ubiquitous for most feldspars. Feldspars that form by rapid cooling display anomalous fading because they are disordered, whereas those that form during slow crystallization and have an ordered lattice structure do not. This is also specified in Aitken (1998). Hütt *et al.* (1993) found that the K-feldspars of granitic origin, did not display TL fading. K-feldspars used in the present study originated from the Tenryu River's upstream, igneous rock zone (Liu *et al.,* 2007), which formed gradually with an ordered lattice structure. Hence, we postulate that the K-feldspars collected in this study should not be affected by anomalous fading. If this is not the case, the effect of anomalous fading would still be minor because the collected samples are young, and Huntley and Lamothe (2001) mentioned that anomalous fading is more severe in older samples.

Luminescence measurements were performed using both a Harshaw Model 3500 Manual Thermoluminescent Detector (TLD) Reader and a Risø 48-sample automated TL/OSL Reader with an internal $^{90}Sr/^{90}Y$ β-irradiation source (delivering 0.12 Gy dose/s). Four aliquots of each sample were mounted on 6 mm (TLD reader) or 10 mm (TL/OSL reader) diameter, stainless-steel discs using silicone spray as an adhesive. To avoid the heterogeneous effect from individual grains (grain-to-grain variation), the monolayer technique was applied, so that each disc contained approximately several hundred feldspar particles. To produce a TL glow curve, samples were measured using a heating ramp rate of 5°C/s (up to 500°C) and were detected though the photomultiplier tubes (TLD reader) or a photomultiplier using a Schott BG39 (infrared absorbing) and a comparatively narrow glass filter, Corning 7-59, combination with a transmission window between 320 and 480 nm. Such a combination effectively excluded luminescence from any quartz and from most plagioclase feldspar from being measured.

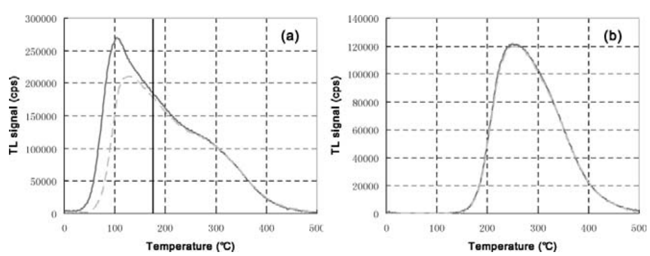

Figure 3. Delayed test for determining the preheating conditions, using thermally bleached sample, S3. The solid line is the TL measurement immediately after 7.2 Gy laboratory irradiation; the dashed line is the TL measurement with a 30 min delay after laboratory irradiation (a) without preheating, and (b) with preheating at 180°C for 10 s.

Experimental Methodology

Before proceeding to the TL measurement, an adequate TL test sequence was examined. In this sequence, a series of TL pretests were investigated first. Among these, the preheating test, used to decide a suitable preheating temperature and duration, was of great importance to drawing a correct luminescence response curve (Aitken, 1998). There are a number of feldspar TL peaks, corresponding to a series of TL traps, which reflect variations in the mineralogy (Duller, 1997). When feldspar is artificially irradiated in the laboratory, many shallower traps are filled, which produces low-temperature TL peak as shown in Figure 3a at around 110°C. A 110°C, TL peak for K-feldspar was also detected by Strickertsson (1985). In general, such low-temperature TL peak does not exist in natural TL signals because of the long storage times in the field. Shallow-trap–related low-temperature TL peaks are unstable, and their signals gradually decay with time. Figure 3a illustrates a delayed test result at two delaying time intervals (0 and 30 min) after a 60 second artificial-dose irradiation on sample S3, which was thermally bleached before the delayed test. It is obvious that with a 30 minute detention, the TL signals decrease dramatically in the low-temperature range, whereas there is no clear TL signal reduction in the high-temperature region. Preheating to a certain temperature can help to remove such unstable artificial TL signals in the low-temperature region. The boundary between low- and high-temperature regions (unstable and stable TL signals) is located around temperature of 180°C, as highlighted by the vertical line in Figure 3a. Hence, a 180°C preheating temperature was chosen for this study. Applying a longer preheating duration might remove useful TL signals, even in the high-temperature region. A preheating duration of 10 seconds was used, which is the same condition that was applied by Wallinga, Murray, and Wintle (2000) and by Blair, Yukihara, and McKeever (2005) in their feldspar tests. Figure 3b shows the same delayed test result as in Figure 3a, but with preheating of 180°C for 10 seconds before the TL measurement. In this Figure, the role of the preheating is clearly demonstrated because there is no distinct variance

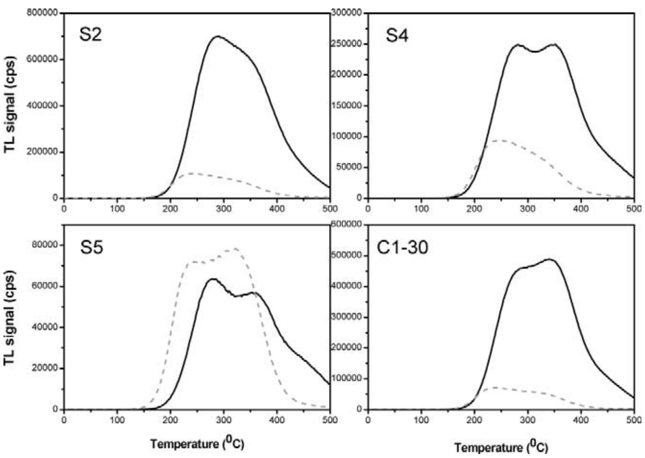

Figure 4. Difference between the natural TL signal (solid line) and the 7.2 Gy test-dose TL signal (dashed line) for several samples S2, S4, S5, and C1-30.

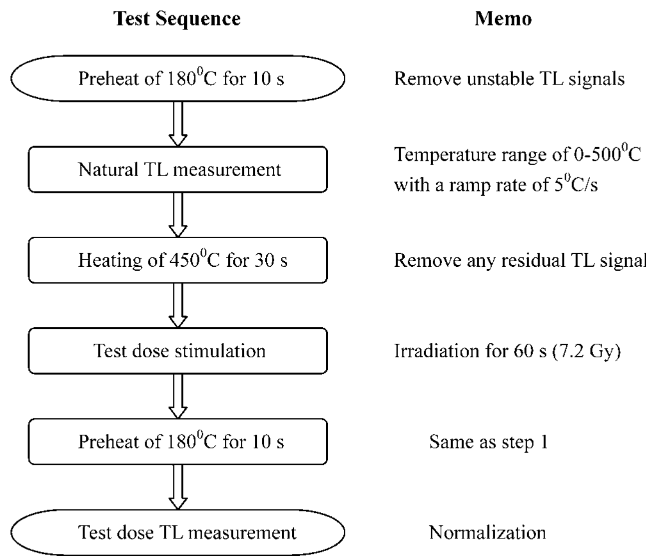

Figure 5. General TL test protocol in this study.

between the TL measurements taken immediately and those taken after a 30 minute delay, which suggests the low-temperature, unstable TL signals were efficiently removed after preheating.

To compare the sample aliquots collected at different locations in the field, normalization of the natural TL signal was needed to compensate for the differences that are inherent in the samples, such as aliquot mass. Therefore, after each natural TL measurement, the sample discs were first heated to 450°C for 30 seconds to remove any residual TL signal (Duller, 1992). Then, each aliquot was irradiated at a laboratory test dose of 60 second (7.2 Gy), and measurements were carried out again to obtain the test dose–induced TL response curve for normalization. The following equation was applied for the natural TL normalization,

$$\text{Normalized natural TL} = \frac{\text{Natural TL}}{\text{Test dose TL}}. \qquad (1)$$

This equation was performed after taking into account the difference between natural and the test-dose TL glow curves. Figure 4 presents a comparison of natural and test-dose TL glow curves for several test aliquots from river sample S3, coast sample S4, dune sample S5, and the underwater sample C1-30 (30 cm below the core surface). There exist clear differences between these natural and test-dose TL curves, such as the curve shape and the peak location, which implies that the natural TL signal cannot be reproduced by simply adjusting the artificial irradiation-dose magnitude. Such differences are assumed to be to the result of the complex natural sediment-transport process. In the field, grain particles undergo repetitive processes of erosion, transportation, and deposition, which induce continuous storage and bleaching of grain TL signals. Hence, the measured, natural TL signal may come from several such cycles. The complex, natural processes can not be reproduced from a single laboratory test-dose irradiation. Shirai, Tsukamoto, and Kondo (2008) also mentioned the influence of such complicated natural process after their OSL measurements. To minimize the effect from the natural/test-dose TL difference, a relatively wide temperature range (200°–400°C) was considered as the average for the test-dose TL signals. Figure 4 shows that this temperature range covers the predominant TL signals. A similar temperature range (250°–400°C) was also applied by Zhang, Li, and Tso (2001) in their TL studies.

Figure 4 also reveals that, for the collected samples, in general, the natural TL signals are much larger than the 7.2 Gy test-dose–induced values. Within these results, dune sample S5 presents the smallest natural TL signal with a magnitude almost equal to the test-dose one. This indicates that the apparent natural dose is about 7.2 Gy for dune sands. If such an apparent natural dose came from natural electron accumulation in the defects as a result of environmental radiation after burial, the age of burial would be about 7,000 years after considering the fairly weak natural radioactivity in Japan, which has a feldspar dose rate of about 0.6–2.1 Gy every thousand years (Watanuki, Murray, and Tsukamoto, 2005). However, that is not the case in this study. As previously mentioned, the target area is a geologically young region, with a formation age of only several hundred years. Hence, we hypothesize that the TL signals of the collected samples, as well as the differences among them, do not come from the limited variance in burial time, but rather from the differences in the sample depositional environments, *i.e.,* aeolian, subaerial, and subaqueous, under which different amounts of sunlight exposure possibilities exist. This subject is discussed further in the "Results and Discussions" section.

Based on the pretests, a generalized TL test sequence was proposed for this study. Figure 5 presents the corresponding test sequence, together with explanations for each step.

RESULTS AND DISCUSSIONS

Based on the proposed test protocol, TL measurements were carried out for all collected field samples. In the follow-

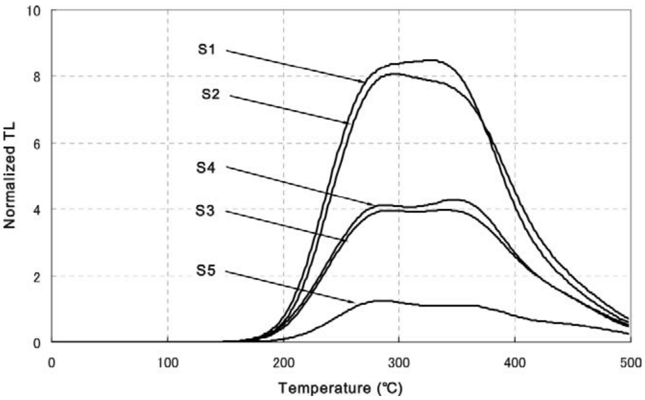

Figure 6. Normalized natural TL glow curves for collected samples at S1 and S2 from Kaketsuka, S3 from the river mouth sand spit, S4 from the Nakatajima Coast, and S5 from Nakatajima Coastal Dune.

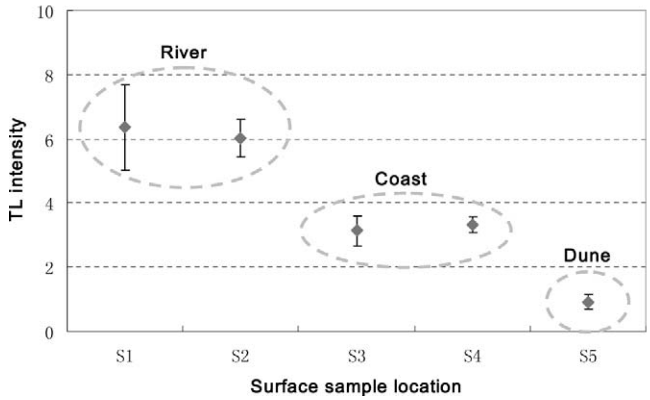

Figure 7. TL intensity (the ratio between the natural and test-dose TL integration over temperature range of 200° to 400°C) and the standard deviations (error bar) for the surface samples (S1–S5).

ing sections, the normalized TL glow curves (the average of four discs for each sample) are presented, and the integration of the signals over the 200–400°C temperatures, together with their standard deviations were calculated for data interpretation and intercomparison. Results are categorized into three groups with respect to their sampling locations, *i.e.,* surface samples (S1–S5), underground samples (G1, G2, and G3), and underwater samples (C1).

Surface Samples

To clarify the spatial distribution of TL properties in the research area, all surface samples, S1–S5, are considered in this subsection. Figure 6 illustrates the normalized TL glow curves for these samples. In this Figure, it is clear that the TL signal is large along the river route (S1/S2) and small at the coastal area (S3/S4). There is no clear difference between S1 and S2. Similar results were also found for the S3 and S4 samples. Compared to the unidirectional river flows (S1/S2), sand particles may be suspended and bleached by sunlight more easily and efficiently under repeated wave motions, especially in the dynamic swash zone (S3/S4), where sediment particles are frequently mobilized by the wave uprush and downwash process. Such TL signal reduction along the coastal region can be clearly observed by comparing the TL curves of S1/S2 and S3/S4. Nevertheless, Rink (2003) observed, along the coastal line, a trend of decreasing residual TL intensity with increasing distance from the sand's primary source. In the present study, and taking the results of S3 (near the source) and S4 (away from the source) into account, there is no obvious difference between them. This is considered to be due to the short longshore distance between S3 and S4 (about 4 km). In Rink (2003), the study area covered a longshore distance of around 150 km. Therefore, in this study, and within the studied area, the measured TL difference should not come from the transport distance of the original source. Figure 6 shows that the TL signal at Nakatajima Coastal Dune (S5) is the minimum, but not at zero. This is due to sufficient solar exposure for many years, determined by considering that the sampling position is located at a coastal dune, where the surface sand is mainly transported in air by blowing wind. Compared with the other surface samples, sample S5 was much less protected from the sunshine because particle movement was induced by aeolian transport. These grains would be expected to be well bleached (Ballarini *et al.,* 2003). However, even after long sunlight exposure, these sand particles did not lose all their TL signals (trapped electrons), and certain natural TL signals remained, which are called the *natural residual TL* in Zhang, Li, and Tso (2001) and in Rink (2003).

To further specify the insight into the grain's inherent natural TL features, the average of the normalized TL glow curve over temperature range of 200°–400°C was calculated. In fact, considering the normalization equation applied here, this approach presents the comparison (the ratio) between the 200°–400°C channel integrations of the natural and test dose TL because normalization was also carried out in the same temperature range. Such a ratio provides a clear indication of the apparent dose. Here, we named this ratio the *TL intensity.* Figure 7 shows the estimated TL intensities, together with their standard deviations, for the surface samples. Similar to the results shown in Figure 6, there were decreases in the TL intensities from S1 to S5. In general, we can classify the data into three groups with respect to the TL intensity, *i.e.,* river (S1/S2), coast (S3/S4), and dune (S5) as specified using three circles. In river group, the TL intensity was about 6, indicating that the river sample had an apparent natural residual dose of around $6 \times 7.2 = 43.2$ Gy; TL intensity of coastal group was around 3, with an apparent dose of 21.6 Gy; whereas the TL intensity was only about 1 for the dune group (with an apparent dose of about 7.2 Gy). Such difference in the TL intensity represents the typical grain properties in terms of its unique depositional environment, under which different light-exposure possibilities existed. A further look at the standard deviations shows that the variance for the dune sample was small, which suggests a relatively uniform distribution of TL signal. This is due to the windblown mechanism by which sand particles are trans-

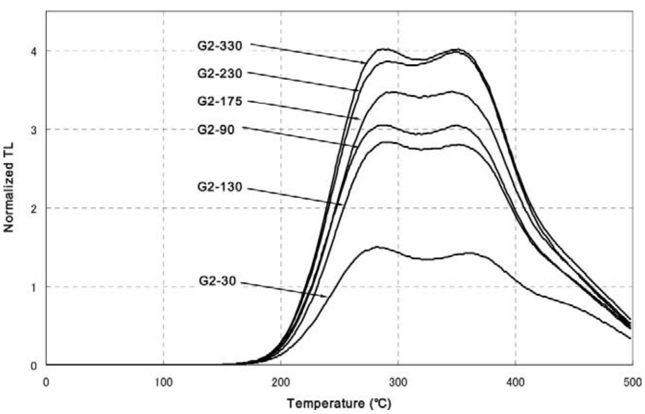

Figure 8. Normalized natural TL glow curves at six different vertical locations along the underground geo-slicer sample G2.

ported in air, providing an equal opportunity to be bleached. On the contrary, sunlight exposure for river particles is more occasional and irregular (mainly during flood events), which results in a large deviation of the measured TL signals. The situation for coastal grains, under repeated wave actions, is in between the other sample groups.

Underground Samples

All underground samples collected in the geo-slicer study at Nakatajima Coastal Dune, *i.e.,* samples G1–G3 were investigated in this subsection to illuminate the coastal dune evolution process. Figure 8 shows the TL glow curves for six vertical locations along sample G2 as illustrated in Figure 9. The line marked G2-30 represents the measured TL values 30 cm below the surface of G2. In this Figure, the TL signal gradually increases with the burial depth. The maximum TL value is found at the deepest location at G2-330, with a peak value around 4, whereas the minimum TL is located at G2-30, with a peak value of around 1.5. Taking Figure 6 into account, it is found that G2-330 presents a similar result as the coastal samples S3/S4, and G2-30 presents a similar trend as the dune sample S5. This implies that the whole coastal dune may consist of sands from two different origins, *i.e.,* the upper windblown sand and the lower wave-induced sand. In between, a mixing layer, with a medium TL signal (G2-90, G2-130, and G2-175), exists. Within the mixing layer, the TL intensity is large in cases in which the coast sand contribution predominates and *vice versa.*

Figure 9 shows the vertical distribution of TL intensities for all geo-slicer samples (left panel). In total, 12 TL samples were measured for various depths at three locations. *T.P.* stands for the average water level of Tokyo Bay, which is a

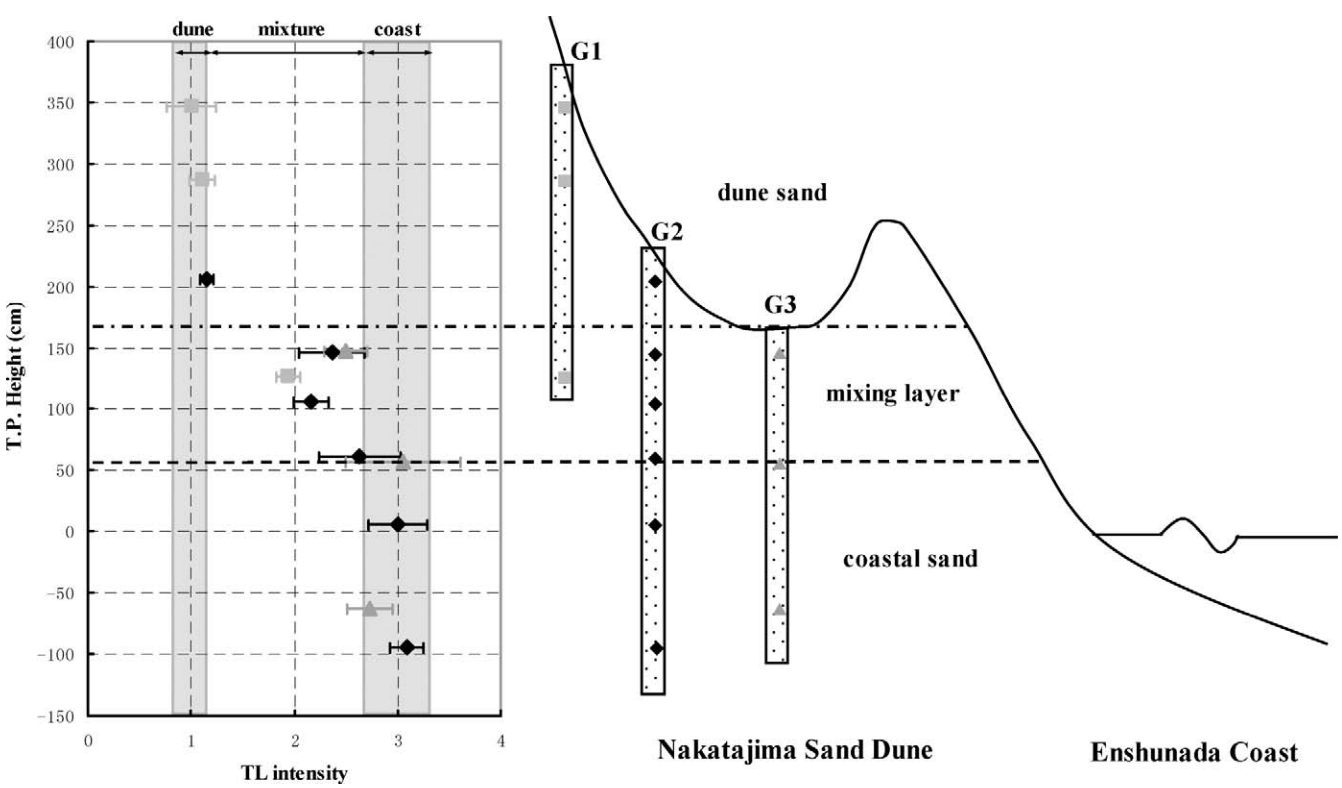

Figure 9. Integrated TL intensity for geo-slicer samples G1 (■), G2 (♦), and G3 (▲), together with the schematic diagram, which specifies the field sampling locations, on the right panel.

standard datum level in Japan. Taking Figure 7 into account, the corresponding TL bands for the dune and coastal sand, with relatively narrow and wide widths, are overlapped in this Figure to facilitate our understanding. Considering the field sampling locations, presented in the right panel of Figure 9, three subareas with different TL intensities can be observed, *i.e.,* an upper aeolian zone, a middle mixing zone, and a lower coastal zone. The horizontal dash-dot line presents a schematic interface between the aeolian and mixing regions, whereas the horizontal dashed line shows a rough boundary between the mixing and coastal regions. Three samples located in the upper layer of samples G1 and G2 are in the aeolian zone, which has a small TL intensity (about 1), with a value similar to that of S5. Therefore, we conclude that these sands are composed of the well-bleached dune sand, which was blown there by the wind. In the lower layer, sample TL intensities are around 3. Considering the sorting criterion presented in Figure 7, this layer consists of relatively poorly bleached coastal sands, which were transported there by wave motion. In between, there exists a mixing layer. The relevant sample TL intensity is within the dune sand and coastal sand scales. Consequently, the vertical configuration of Nakatajima Coastal Dune can be described as stratified, with dune sand and coastal sand at two ends and a mixing layer in between. Such stratified distribution was also observed by Takagawa *et al.* (2008) in their ground-penetrating radar images as well as in their subsequent particle-size analysis. They found that the high-tide level at Nakatajima was around T.P. 90 cm, which is located just within the mixing-layer range proposed by these TL measurements. Taking wave actions into account, the mixing-layer range specified by the TL test is verified.

Considering the historical evolutionary process of the Nakatajima Coastal Dune, as mentioned previously, with its sediment source in the Tenryu River watershed, the sand was transported alongshore by nearshore waves and currents. During the process of dune generation over about 200 years, certain sands were relocated to the top layer through the wind blowing, during which, their TL signals decrease; whereas other sands remained at the bottom and keep their TL signals almost unchanged. The stratified structure of Nakatajima Coastal Dune, again, demonstrates that the measured, natural TL signals probed the various sediment depositional environments.

Underwater Samples

Up to now, the measured TL samples were all ground ones, either subaerial or underground. As for surface samples, S1–S4, they may be covered by water during flooding or swashing. However, such water coverage is intermittent, and these sand particles may be directly exposed to sunshine at most times. In this subsection, the underwater samples will be investigated to illuminate the formation process in front of the Tenryu River mouth and to demonstrate how the water body plays its role as a filter on sample TL signals.

Figure 10 shows the corresponding results for samples from a 10-m-long boring core (C1) extracted at a 10 m water depth in front of the Tenryu River mouth. Four positions were considered for TL studies, *i.e.,* 30 cm, 260 cm, 640 cm, and 980 cm beneath the core surface. It was found that the TL intensities of C1-30 and C1-260 were almost the same, with values larger than that of the river samples, S1/S2. Considering that the water body plays the role of a light attenuator, the underwater samples may present a larger TL value than that of surface samples because subaerial exposure produces a more efficient bleaching than that of underwater exposure. At the same time, samples C1-640 and C1-980 have the similar TL values, which are in between that of S1/S2 and S3. This may be ascribed to a fairly complex sediment-movement process in front of the river mouth, which caused a rather dynamic evolution of the coastal bathymetry as mentioned previously. The boring-core constituent may come from various sand contributions under different depositional environments, such as river discharge, with a large TL intensity, and coastal sand, with a small TL signal. At the same time, offshore/longshore sand movement may also need to be considered. The development of the seabed stratum is accompanied by a mixing process of these sand fractions. At the same time, influence from the collapse/deformation of the river mouth sand spit/shoreline should also be taken into account. Such an event is not unpredicted after a typhoon, which struck in the summer, with accompanying river flooding (Liu, Tajima, and Sato, 2008). Therefore, the TL signal of C1 samples may reveal such mixing processes from different sands with various TL intensities. Therefore, it is assumed that the formation of the sediment stratum at C1 is very complex, and such processes are somewhat unpredictable and need to be investigated carefully and comprehensively.

A further look at the shape of all TL glow curves in Figures 6, 8, and 10 shows a clear difference between the underwater samples and other ones. In general, two TL glow-curve peaks can be observed in the temperature range of this study. One is around the 290°C temperature, and the other is at 350°C. For the underwater samples, the high-temperature TL peak (HTLP) has a larger value than the low-temperature TL peak (LTLP); whereas a different result, with HTLP being more similar to the LTLP, is found

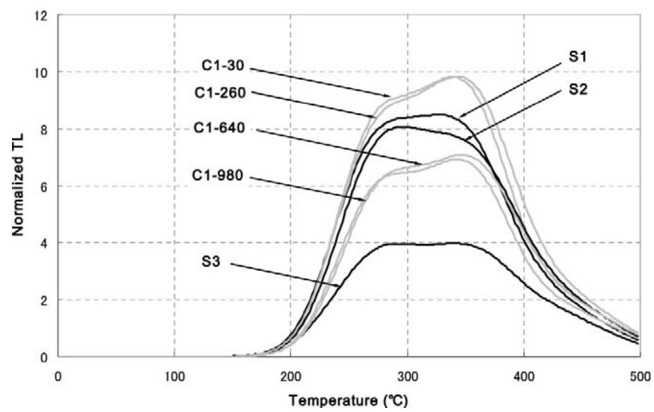

Figure 10. Normalized natural TL glow curves for underwater sample C1 (four positions at 30, 260, 640, and 980 cm below the surface), together with surface samples, S1–S3.

for ground samples. Spooner (1987) and Aitken (1998) demonstrated that water was particularly effective at filtering ultraviolet (UV) radiation and that the UV components are only weakly present in the solar radiation spectrum after passing through seawater. As for quartz particles, they found that visible light only reduces the LTLP. On the contrary, UV wavelength can diminish both. In the present investigation with feldspar, similar results were revealed. During the natural sediment-transport process, loss of TL signals mainly comes from exposure to light, as mentioned formerly. Such eviction process is also related to the light wavelength, *i.e.,* the quantum energy (Aitken, 1998): the shorter the wavelength, the further toward the UV end of the spectrum, the more rapid/effective the eviction. Different TL peaks may also relate to the different trap deepness, *e.g.,* deep traps, corresponding to the HTLP, demand high quantum energy (UV components) to be bleached. Because the seawater acts as a UV filter, only allowing visible sunlight components to penetrate down to the seabed, the bottom particles are only bleached by visible light to evict the relatively shallow traps, *i.e.,* reducing the LTLP, but leave the HTLP almost unchanged. Hence, a high HTLP, together with a low LTLP, is observed for underwater samples. As for the ground samples, they are exposed to both visible and UV light, which decreases LTLP and HTLP simultaneously. Therefore, relatively uniform LTLP and HTLP are observed.

CONCLUSIONS

Investigation of the river/coastal sediment transport was carried out based on the TL properties of natural feldspar. After a series of pretests, an appropriate TL measurement protocol was proposed for this study. Subsequently, that protocol was applied to the study of the sediment movement process along the Tenryu–Enshunada fluvial system through collected field samples at various locations. In the target area, the source of sediments is the Tenryu River watershed. In view of the young age of the investigated area, natural TL difference in the present study does not come from the limited burial time variance, which is within several hundred years. Rather, the natural TL difference is caused by the sample depositional environment under which different possibilities of sunlight exposure exist. The main conclusions of this study are summarized as follows:

(1) After analysis of the surface samples, three groups of sediment particles were categorized in the research area with different natural TL intensities, *i.e.,* river sand, with a large TL signal; coastal sand, with a medium TL signal; and dune sand, with a small TL signal. This demonstrates the influence of the sample environment. That is, poor bleaching for river sand (unidirectional transport due to river flow), medium-bleaching for coastal sand (multidirectional movement due to wave/current actions), and complete bleaching for dune sand (full-light exposure by aeolian transport).

(2) Investigation of the underground TL samples from a geoslicer study implies that the vertical structure of the Nakatajima Coastal Dune can be described as a stratified configuration, with windblown dune sand and wave-induced coastal sand located at the top and bottom of the dune, respectively, together with a mixing layer in between.

(3) After considering the underwater samples extracted in front of the Tenryu River mouth, a rather complex sediment movement pattern is revealed, which is affected by various factors and needs to be investigated carefully and comprehensively. Influence from the seawater, acting as an ultraviolet filter, can be observed from the difference in TL spectra. The high-temperature TL peak is larger than the low-temperature TL peak for underwater samples, whereas these two peaks are almost the same in ground samples.

As mentioned at the beginning, nearshore sediment-movement investigation, based on the grain's TL properties, is still in its early research stage for coastal-engineering applications. Further studies on particle natural TL signals are planned for a broad area, which covers both the upstream river area and the coastal area away from the river mouth. To acquire a quantitative insight into the sediment movement process in a fluvial–coastal system, sediment dating, *e.g.,* using OSL technique, will also be considered.

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