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Millennial-scale reworking of tephra in alluvial to shallow marine settings: Distinguishing pseudo-isochrons from genuine ones

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ABSTRACT

Primary tephra layers can provide isochrons in a stratigraphic sequence. Such isochrons are powerful tools in terms of correlation and chronology of strata, and they constrain a chronological framework for geology, geomorphology, archaeology and palaeo-environmental studies in the Neogene to Quaternary. However, reworking processes can re-distribute tephra materials in both time and space, so that a given tephra can form a new discrete layer later in the depositional sequence, or it can be distributed in low concentrations (no visible layers, i.e., crypto-tephras) over a range of different stratigraphic horizons. The present study, based on sedimentological, petrographical, and geochemical analyses of reworked tephras in Japan, evaluates the duration and persistence of reworking and the tephra mobilisation and delivery to watersheds. Furthermore, it discusses how a unique isochron can be constructed from tephra distribution in a sedimentary sequence. Examples presented here are from fluvial and deltaic sequences in the Japanese Quaternary, which contain several visible tephra layers and a certain amount of tephra materials from multiple sources at different stratigraphical horizons. In the Niigata Plain, 5.4 ka Numazawako tephra material continued to be reworked for more than 4000 years after the eruption of Numazawa volcano, and was re-deposited as reworked pumice grains consisting of a “visible” tephra layer in delta front deposits. Mixed tephra materials originating from an earlier eruption of Numazawa volcano and eruptions from other calderas were also identified. In the Tsugaru Plain, post-2.5 ka subsurface deposits have >10% glass shards content throughout the sequence. Glass shards were derived from several different tephra materials, such as those from the most recent eruption of Towada volcano (AD 915), and earlier caldera forming eruptions (30 ka, 15 ka). Some of the glass shards probably originated from erosion of exposed Pliocene pyroclastic bedrock. Thus, tephra reworking processes in alluvial to shallow marine settings can continue long after an eruption has ended, and can persist even during inter-eruptive (i.e., background sedimentation) periods. As tephra reworking involves complicated processes, careful observation and interpretations are necessary to evaluate whether tephra materials can truly provide an isochron for the strata in which they are found to exist.

1. Introduction

Tephra, when deposited primarily, usually represents a sharp isochron to relatively wide areas such as in mountainous and hilly areas, alluvial plains, and marine settings. Fingerprinting of each tephra and comparison by other dating methods (e.g., ^{14}C, K–Ar, fission track, and OSL dating) to tephra deposition time therefore provides an important clue for correlation and chronology of strata, and helps in constructing a chronological framework for geology, geomorphology, sedimentology, archaeology, and palaeo-environmental studies, especially in the Neogene to Quaternary. In Japan, well-developed and high-resolution tephro-stratigraphy and -chronology defining detailed isochrons (Yoshikawa, 1976; Kurokawa, 1999; Machida, 1999; Satoguchi et al., 1999; Machida and Arai, 2003; Nagahashi and Satoguchi, 2007; Satoguchi and Nagahashi, 2012) have often been used for sedimentary facies analysis and sequence stratigraphy, biostratigraphy, and palaeo-environmental studies (e.g., Ito, 1995; Urabe et al., 1995).

However, when sedimentologists/stratigraphers encounter tephra-bearing strata, interpretation of tephra analysis based on

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petrography, geochemical characterisation, origin, and correlation tends to be outsourced to a tephra specialist. Those tephra specialists are sometimes unfamiliar with the stratigraphic and depositional setting and inattentive to subaqueous (fluvial, lacustrine and marine) tephra transport and depositional mechanisms, because they focus on characterising tephra by petrography and chemistry. Both tephra specialists and tephra users (e.g., sedimentologists) tend to believe that tephra material and tephra beds can be usually of primary (often of airborne) origin, especially when there is a "discrete" visible tephra bed. However, a tephra layer cannot always be assumed to mark the time of an eruption, because tephra can be reworked and re-distributed into different time and space (Nakayama and Yoshikawa, 1997; Kataoka and Nakajo, 2002; Kataoka, 2005; Kataoka et al., 2009), and such reworking can produce a new discrete layer or a dispersed crypto-tephra at a stratigraphic horizon that differs from that of the primary tephra deposition.

This paper reviews and discusses reworking of tephra materials that has been common during the Holocene in alluvial to shallow marine environments in Japan. Such environments offering alluvial to coastal plains have usually been centres of habitation and cultivation for more than thousands of years. Being in a volcanic arc setting, there is high possibility that reworked tephra layers or dispersed crypto-tephra can also be found in many archaeological sites, too. The examples dealt with in this paper are from the Holocene Niigata (Echigo) and Tsugaru Plains, northeast Japan. These two areas are alluvial-coastal plains in Honshu Island, facing the Sea of Japan and having active caldera volcanoes in their catchments. Hence, these fluvial to shallow marine systems have largely been episodically affected by volcanism during the Holocene. This paper aims to evaluate the degree of perennial tephra reworking in background sedimentation in such catchments, to assess the abundance of both visible and invisible tephra in these sediments, and then to elucidate how to extract correct ages and origins from reworked and mixed tephra assemblages.

2. Methodology for tephra analysis of sediment cores

Analyses of tephra layers and crypto-tephras in sediment cores described in this paper consist of 1) grainsize distribution and petrographical observation, and 2) electron probe microanalysis (EPMA) for glass shards and pumice. Sediment cores from two study areas (the Niigata and Tsugaru Plains) and their geological background for two examples are discussed later in this paper.

2.1. Sampling, petrography and grainsize distribution

Tephra analyses were carried out on four sediment cores from the Niigata Plain and one from the Tsugaru Plain. Core samples from the Niigata Plain were cut and sampled with approximately 50 cm intervals (except for TA-1 core, ~100 cm), whereas core samples from Tsugaru Plain were collected with approximately 10 cm intervals. The sampling interval was closer where changes of facies and grainsize were distinct. Dried samples were wet-sieved and then separated by grain fractions of >1/4 mm, 1/4–1/8 mm, 1/8 mm–1/16 mm, and <1/16 mm, and then the mass of each fraction was measured to show grainsize distribution in individual samples. Grain point counts were carried out for >200 grains in 1/8 mm–1/16 mm size after being mounted in epoxy resin or thermo wax on a slide glass. Glass shards content was then estimated. Glass shards were classified into six types, i.e., 1) Ha-type: platy and plain (bubble-wall type); 2) Hb-type: bubble-wall type but with more stretched bubbles; 3) Ta-type: pumiceous, porous; 4) Tb-type: fibrous; 5) Ca-type: intermediate between Ha and Ta; 6) Cb-type: intermediate between Hb and Tb, after Yoshikawa (1976). In addition, blocky shards, and brown coloured or obsidian glass, were observed in samples from the Tsugaru Plain.

Sediments from the Niigata Plain contain marked amounts of pumice fragments. Pumice grains for each sample in >1/4 mm size fraction were counted under a binocular microscope to estimate the pumice content. Because sand content can vary in individual samples, to assess pumice contents in a bulk sample, "pumice index" is introduced here and defined as the product of pumice content (%) multiplied by percentages of >1/4 mm size fraction in total sediments. For instance, if a sample occupies 50% of >1/4 mm size fraction with 20% of counted pumice grains in the fraction, then the pumice index is 0.1. Whereas, if a sample has 10% of >1/4 mm size fraction and 30% of pumice grain, the index is 0.03. The former example shows higher value even the percentage of counted pumice grains in the same fraction is lower. This "pumice index" is realistic because it matches well with visual observation and description of pumice appearance in cores.

2.2. Major element composition of glass shards and pumice

Major element composition of glass shards and/or glassy part of pumice grains was measured using the electron microprobe. Samples were selected from horizons with higher pumice index (for Niigata Plain only), or where with high content of glass shards, or where with changes in facies and grainsize. Approximately 35–50 points were measured for each sample. Samples from the Niigata Plain were measured with a WDS system (JEOL JXA8600) at Niigata University. Beam current was 0.12 nA at 15 kV accelerating voltage and a beam diameter is 5 μm. Data were corrected using the ZAF method (Statham, 1979). At Fukushima University, samples from the Tsugaru Plain were analysed by a SEM-EDS system (JEOL JSM-5800LV + Oxford INCA x-act SDD) with a beam current of 0.3 nA at 15 kV accelerating voltage and a scanning area of 5 μm × 5 μm. Data correction and equations are based on comparison with the results of known standard glass shards measured by XRF (Nagahashi et al., 2003).

3. Niigata (Echigo) Plain: deltaic tephra reworking following the 5.4 ka Numazawako eruption

3.1. Geological setting

Numazawa volcano hosts ~2 km diameter caldera lake at the elevation of 475 m ASL (above sea level). The most recent eruption occurred at ca. 5 ka. The volcano is located about 50 km west of the volcanic front (i.e., on the back arc side) of the northeast Honshu arc in northeast Japan (Fig. 1A; Yamamoto, 2003). The Numazawako eruption started with an emplacement of ~4 km^3 dacitic non-welded ignimbrite, which was followed by a dacitic Plinian eruption (0.4 km^3); an andesitic phreatomagmatic eruption (0.2 km^3); and an andesitic Plinian eruption (0.2 km^3) without any periods of major quiescence (Yamamoto, 1995, 2003; Masubuchi and Ishizaki, 2011). Transported by prevailing westerly winds, fallout from the eruption was concentrated east of the volcano (Yamamoto, 1995, 2003). ^{14}C dating applied to Numazawako eruptive units shows ages between 4430 ± 70 to 4760 ± 90 BP, and estimated age of the eruption is ~3400 BC (Yamamoto, 2003). The thick ignimbrite was valley-confined and therefore the unit is concentrated in the adjacent Tadami River valley and its tributaries (Fig. 1A). The Tadami River joins the Agano (Aga) River about 35 km downstream of the caldera and then flows more than 100 km, across the Niigata Plain, and finally enters to the Sea of Japan.