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Quaternary tephrochronology and deposition in the subsurface Sacramento–San Joaquin Delta, California, U.S.A.

Katherine L. Maier [a,*], Emma Gatti [a,b], Elmira Wan [c], Daniel J. Ponti [a], Mark Pagenkopp [d], Scott W. Starratt [e], Holly A. Olson [c], John C. Tinsley [a]

[a] U.S. Geological Survey, Earthquake Science Center, 345 Middlefield Road Mail Stop 977, Menlo Park, CA 94025, USA
[b] Planetary Surface Instruments Group, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[c] U.S. Geological Survey, Geology, Minerals, Energy, and Geophysics Science Center, 345 Middlefield Road Mail Stop 975, Menlo Park, CA 94025, USA
[d] California Department of Water Resources, 3500 Industrial Boulevard, West Sacramento, CA 95691, USA
[e] U.S. Geological Survey, Volcano Science Center, 345 Middlefield Road Mail Stop 910, Menlo Park, CA 94025, USA

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ABSTRACT

We document characteristics of tephra, including facies and geochemistry, from 27 subsurface sites in the Sacramento–San Joaquin Delta, California, to obtain stratigraphic constraints in a complex setting. Analyzed tephra deposits correlate with: 1) an unnamed tephra from the Carlotta Formation near Ferndale, California, herein informally named the ash of Wildcat Grade (<~1.450 to >~0.780 Ma), 2) the Rockland ash bed (~0.575 Ma), 3) the Loleta ash bed (~0.390 Ma), and 4) middle Pleistocene volcanic ash deposits at Tulelake, California, and Pringle Falls, Bend, and Summer Lake, Oregon, herein informally named the dacitic ash of Hood (<~0.211 to >~0.180 Ma). All four tephra are derived from Cascades volcanic sources. The Rockland ash bed erupted from the southern Cascades and occurs in up to >7-m-thick deposits in cores from ~40 m subsurface in the Sacramento–San Joaquin Delta. Tephra facies and tephra age constraints suggest rapid tephra deposition within fluvial channel and overbank settings, likely related to flood events shortly following volcanic eruption. Such rapidly deposited tephra are important chronostratigraphic markers that suggest varying sediment accumulation rates in Quaternary deposits below the modern Sacramento–San Joaquin Delta. This study provides the first steps in a subsurface Quaternary stratigraphic framework necessary for future hazard assessment.

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Introduction

Tephra deposits (including volcanic ash, pumice clasts, lapilli, and glass shards) are important correlation tools that can be used to constrain time surfaces in sedimentary successions (e.g., Sarna-Wojcicki, 2000; Lowe, 2008, 2011; Nooren et al., 2009; Addison et al., 2010; Salisbury et al., 2012). Additionally, detailed description and interpretation of tephra deposits including facies analysis can lead to a better understanding of depositional processes (e.g., Nakayama and Yoshikawa, 1997; Kataoka, 2005; Kataoka et al., 2009; Manville et al., 2009; Lowe, 2011; Gatti et al., 2011, 2013; Tripaldi et al., 2011). In this study, analysis and correlation of identified tephra deposits aid subsurface chronostratigraphic correlations and depositional environment interpretations in the complex setting of the Sacramento–San Joaquin Delta (also referred to herein as the delta), California, an important area for natural hazards, freshwater supply, ecosystems, tectonics, and sediment transport and deposition.

The Sacramento–San Joaquin Delta includes the lower reaches of the Sacramento and San Joaquin rivers and the confluence of these two rivers upstream from San Francisco Bay (Fig. 1). Rivers presently drain the interior of central and northern California into the delta (~1400 km^2) and create a region of wetlands that have been anthropogenically modified into agricultural lands beginning in the mid-19th century (Jackson and Paterson, 1977; Logan, 1990; Ingebritsen et al., 2000). The modern Sacramento–San Joaquin Delta is dominated by peat deposits, developed during the Holocene, and intervening fluvial channels (e.g., Drexler et al., 2009, 2014). Agricultural development and farming of peat soils have led to oxidation and compaction of peat soils and subsidence of the region below sea level (Deverel and Rojstaczer, 1996; Ingebritsen et al., 2000; Mount and Twiss, 2005; Coons et al., 2008). Levees and a complex system of waterways have been constructed to keep saline sea water out of the delta, protect shipping lanes, prevent destructive flooding of the islands, and maintain California's freshwater supplies (Jackson and Paterson, 1977; Ingebritsen et al., 2000; Burton and Cutter, 2008). Only the westernmost modern Sacramento–San Joaquin Delta experiences brackish water conditions, and this has been consistent into the Pleistocene and throughout the Holocene (Byrne et al., 2001; Starratt 2002, 2004; Drexler et al., 2014). During Pleistocene climatic fluctuations, the Sacramento–San Joaquin Bay-Delta encompassed fluvial systems, with the modern drainage configuration being established by ~0.6–0.4 Ma (Barnard et al., 2013 and references therein).

* Corresponding author at: U.S. Geological Survey, Pacific Coastal and Marine Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA.
E-mail address: kcoble@usgs.gov (K.L. Maier).

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The modern Sacramento–San Joaquin Delta (Fig. 1) is the epicenter of numerous risk assessment, land management, water resource, infrastructure, and agricultural issues (e.g., Ingebritsen et al., 2000) because the fresh water supply for >2/3 of California moves through the delta waterways. The delta contains abundant agriculture, diverse wetland ecosystems, and growing urban areas. Levees within the delta, and the populations, infrastructure, freshwater, and agriculture behind them, are potentially at risk of failure related to shaking and liquefaction during an earthquake (Finch, 1988; Wong et al., 2006; Burton and Cutter, 2008; Real and Knudsen, 2009; Real et al., 2010). Seismic activity is possible along numerous faults in the adjacent San Francisco Bay area, where several large-magnitude (>*M*6.0) earthquakes have occurred in historic times (e.g., Yu and Segall, 1996; Unruh and Krug, 2007; Unruh et al., 2009). Chronostratigraphic markers, such as tephra layers, are critically important for calibrating Quaternary stratigraphic relationships necessary to address seismic and liquefaction hazard assessment, infrastructure planning, and water management in the delta.

Existing documentation and interpretation of deposits in and below the modern Sacramento–San Joaquin Delta are focused on surficial exposures and shallow boreholes (<15 m) (e.g., Atwater, 1982; Goman and Wells, 2000; Brown and Pasternack, 2004; Drexler et al., 2014). In particular, studies have addressed the increased subsidence in delta islands with respect to reclamation, agriculture, peat soils, and wetland ecosystems (e.g., Deverel and Rojstaczer, 1996; Jassby and Cloern, 2000; Drexler et al., 2007), and detailed chronology of small regions has focused on the Holocene (e.g., Ingram et al., 1996; Goman and Wells, 2000; Byrne et al., 2001; Starratt, 2002, 2004; Brown and Pasternack, 2004; Wright and Schoellhamer, 2005; Drexler et al., 2014). Although a geologic context for the Quaternary of the region has been established from surface mapping (e.g., Atwater, 1982; Lettis, 1982), additional subsurface chronostratigraphic markers are needed to extend Quaternary stratigraphic framework into deposits buried below the modern Sacramento–San Joaquin Delta. Buried Pleistocene and Holocene deposits contain material properties that will direct ongoing infrastructure planning and also may record potential fault activity in the region. Age constraints for these buried deposits are largely lacking and are needed for chronostratigraphic correlation, which in turn, supports hazard mitigation planning.

Tephra layers are preserved in deposits buried in the Sacramento–San Joaquin Delta (Maier et al., 2014). Abundant Quaternary volcanism in the western U.S. (Luedke and Smith, 1991) has led to sampling and analyses of numerous tephra layers from the region (Fig. 2), and results from thousands of samples are available in the U.S. Geological Survey (USGS) Tephrochronology Project database. The extent of primary tephra distribution, characteristics, geochemistry, and age constraints have been established for significant regional tephra (Fig. 2), including the Rockland ash bed (Sarna-Wojcicki et al., 1985; Lanphere et al., 2004) and the Loleta ash bed (Sarna-Wojcicki et al., 1987, 1989, 1991). Tephra are preserved and sampled in recent California Department of Water Resources geotechnical borehole cores in the Sacramento–San Joaquin Delta, potentially providing key chronostratigraphic markers.

In this study, we address these questions: 1) Which Quaternary tephra are preserved in buried deposits below the modern Sacramento–San Joaquin Delta?, 2) Do tephra record transport and deposition via fluvial processes?, and 3) Are individual tephra preserved or pervasively mixed with other tephra deposits? We hypothesize that individual tephra layers are preserved, and that a percentage of these tephra were primarily transported and widely deposited in fluvial systems, shortly following eruption, resulting in chronostratigraphic surfaces. Recognition of numerous new deposits of marker tephra buried below the modern Sacramento–San Joaquin Delta provides a temporal and spatial framework that supports interpretations of depositional environments and varying sediment accumulation rates. These new insights underpin subsurface correlations that will be an important part of future development, planning, and seismic hazard assessment in the Sacramento–San Joaquin Delta. Additionally, the identification, correlation, and depositional interpretation of tephra from geotechnical borehole samples here suggest that this integrated approach could also aid subsurface chronostratigraphic correlation in other fluvial-deltaic settings where geotechnical samples exist or where boreholes are being drilled.

Methods

Available existing data

From 2009 to 2012, the California Department of Water Resources (CDWR) drilled over 128 geotechnical boreholes across the Sacramento–San Joaquin Delta. The drilling was motivated by proposals to construct a subsurface water conveyance system along an approximate north–south-oriented alignment from south of Sacramento to Clifton Court Forebay (i.e., California Department of Water Resources et al., 2013). Geotechnical drilling and sampling procedure is described in Maier et al. (2014) and uses the Unified Soil Classification System (USCS) (American Society for Testing and Materials, 2007). During CDWR geotechnical drilling in the Sacramento–San Joaquin Delta, meters-thick units of white, angular, sand and silt-size grains, and rounded, pebble-size pumice grains were first recognized as potential tephra. Re-examination of geotechnical logs by CDWR following drilling led to additional recognition of potential tephra.

Geologic core descriptions and facies designations

In this study, CDWR cores were examined at centimeter scale to provide stratigraphic context for tephra samples and to document subtle differences in geologic parameters, such as grain size, sedimentary structures, Munsell color, etc. Geologic core descriptions followed methods detailed in Maier et al. (2014), wherein comprehensive logs of tephra-bearing cores and additional cores lacking tephra are also available. High-resolution logging was conducted for over 170 m of retained punch core samples from 27 boreholes in the northern and central regions of the delta in which tephra are identified. Detailed visual re-examination of punch core and SPT samples identified additional thinner, potential tephra-bearing units containing angular silt and sand-size grains, a characteristic texture, and generally, a lighter color than surrounding deposits.

Detailed observations in the form of geologic core logs, CDWR USCS logs, and CDWR photos are used to determine the thickness of tephra deposits, define tephra facies, and interpret processes of transport and deposition. Tephra deposits in the subsurface Sacramento–San Joaquin Delta are grouped into three facies based on grain size, thickness, and concentration of volcanic-derived grains. Variation within facies is described in terms of subfacies, which contain enough similar overall characteristics to be grouped as a single facies but display differing internal structures or subtle grain-size changes.

Tephra sampling and analyses

We use tephra nomenclature of Lowe (2008; 2011) wherein the term tephra encompasses volcanic ash (grains < 2 mm in diameter) and pumice lapilli (grains 2–64 mm in diameter). Both ash and pumice deposits contain volcanic glass shards < 2 mm in diameter. Potential tephra-bearing units were identified based primarily on a distinct texture, characteristic gray to white color, and presence of glass shards in the tephra units, in contrast to surrounding non-tephra-bearing deposits. Tephra units were also identified by the presence of large rounded pumice grains, distinct from sub-angular sand and gravelly sand deposits.

Ten tephra samples from eight of the 27 CDWR boreholes containing tephra were analyzed for glass shard chemistry (Fig. 1B, C; Table 1). Where possible, samples were obtained from punch cores in order to generate a high-resolution record of stratigraphic and depositional context. Six samples that each contained thick tephra deposits from depths ~40 m subsurface were analyzed from four boreholes near Hood, California. Three samples from three boreholes in the northern to central