1. Introduction

The term ‘tephra’ is used for all airborne solid material derived from volcanic eruptions (Þorarinsson, 1944). Tephrochronology uses discrete layers of tephra within sedimentary successions as an indicator of age, which is facilitated by the fact that volcanic eruptions usually are well datable themselves, and that their tephras are often quite certainly identified by means of the chemical composition of glass shards or minerals through electron microprobe analysis (Izett, 1981; Sarna-Wojcicki & Davis, 1991). Tephrochronology has evolved into an important tool in geochronology (Froese et al., 2008), particularly where tephra beds are frequent and distinguishable such as in Iceland (Þórarinsson, 1979), New Zealand (Vucetich & Pullar, 1969), and in the western U.S.A. (Izett, 1981; Sarna-Wojcicki & Davis, 1991). It is a major tool for dating and synchronizing sedimentological archives (Lowe, 2011).

However, occasionally tephras are admixed to other substrates in a way that their identification gets difficult, especially if their glass shards have been weathered during subsequent pedogenesis. A famous case is the Alłerød Laacher-See Tephra (LST) Complex in Central Europe. Its known distribution in the form of discrete layers is depicted in Figure 1. Though not preserved as a layer anymore, it is known to have been spread much farther. This knowledge stems from heavy-mineral analyses: due to the fact that the tephra contains a rather unique combination of minerals (typically brown amphibole, titanite, and aegirine-augite), it may be identified even without discrete layers and preserved shards. Figure 1 gives some examples from the literature and from own unpublished analyses, demonstrating the possibility to trace the tephra com-
ponents outside of the distribution of discrete layers. Since Schönhals (1957) and Stöhr (1963), Semmel has published a vast number of analyses of LST minerals in the uppermost layer of slope deposits from the mountains around Lake Laach (most recently: Semmel, 2003; Semmel & Terhorst, 2010); they cannot be depicted here in detail because of scale.

Another example of tracing the distribution of tephra components aided by heavy-mineral analyses was given by Kleber (1999). He reported cummingtonite as a heavy mineral traces of which may frequently be found in certain layers of slope deposits in and around the northern Great Basin, U.S.A. Cummingtonite may be a stratigraphic marker mineral in that area. It was yielded by Mt. St. Helens, with the first eruption known to contain this mineral (Mullineaux, 1986) around 50,000 years ago (Berger, 1991). Another cummingtonite-bearing eruption occurred around 13,000 years ago (Mullineaux, 1986). Kleber (1999) assumed that the two deposits containing this mineral may be approximately correlated chronologically with those prominent eruptions, because the principles of tephrochronology may be applied to cryptotephra as well as to discrete layers (Lowe, 2011). However, this interpretation certainly is less reliable than the previous one regarding Laacher-See Tephra, because it is based on just a single, though rather uncommon, mineral instead of a combination of three.

1.1. A new approach

Here I present a new approach to use heavy-mineral analysis as a tool for tephrochronology, inasmuch as I do not attempt tracing tephra constituents beyond the known regional distribution of the tephra layers, but try to locate the first occurrence of constituents of a particular tephra within a single, though complex, sediment profile.

Provided a tephra layer appears to be uncontaminated with other material admixed during reworking of a first-deposited tephra layer, the danger of reworking of tephra material from another location considerably after its primary deposition is rarely considered, because it is usually assumed that the tephra necessarily would have become mixed with the much more voluminous local clastic load; rather, it is assumed that reworking could only have occurred shortly after the initial eruption and deposition of the tephra (Sarna-Wojcicki & Davis, 1991). Thus, in the case of discrepancies with independent age estimates, the date Fig. 1. Distribution of Laacher-See Tephra layers in Central Europe. LST layers: distribution of discrete layers of Laacher-See Tephra of at least 0.5 cm thick (after Van den Bogaard & Schmincke, 1985); LST found: admixed heavy minerals of the Laacher-See Tephra found in the uppermost layer of a slope deposit (selected cases, with reference); no LST found: LST minerals not found in a sample of at least 200 transparent grains (unpublished own analyses).
provided by an uncontaminated tephra layer is usually given preference (e.g., Davis et al., 1986).

1.2. The La Sal Mountains tephra layer

A tephra layer, in the following referred to as the La Sal Mountains (LSM) tephra layer, found in the north-western LSM, Utah, U.S.A. (located 38°36’N, 109°22’30”W, at an elevation of 2130 m a.s.l., on a 22° steep slope), is exposed by a road cut of the Manti-La Sal circuit (Figs 2 and 3). It has previously been taken for a mature carbonate-enriched soil horizon due to its bright colour (M. Ross, mapping geologist of the UGMS, pers. comm., 1990). The relative position of such a mature calcic horizon appeared unlikely in the light of previous stratigraphic evidence from nearby areas (Kleber, 1994a); upon closer look, this layer turned out to consist of tephra. The chemical composition of its glass shards is close to that of the approx. 1.65 Ma old (Spell et al. 1990) Guaje Tephra, derived from the Jemez Mountains, New Mexico. An alternative match is the approx. 1.25 Ma old (Phillips et al., 2007) Tsankawi Tephra from the same mountain range (Slate et al., 2007). However, particularly the similarity in iron content (Table 1) supports the correlation of the LSM tephra layer with the Guaje rather than with the Tsankawi Tephra (A.M. Sarna-Wojcicki, USGS, written comm., 1993).

![Fig. 2. Western United States with locations of the La Sal Mountains, Utah (open circle) and the Jemez Mountains, New Mexico (closed circle).]

Table 1. Electron microprobe analyses of glasses from the LSM Tephra and the closest matches, the Guaje and the Tsankawi Tephra. See Sarna-Wojcicki et al. (2005) for sample preparation and analytical methods. Analyst C.E. Meyer, US Geological Survey, Menlo Park, sample NLSM–109. Values given are weight-percent oxide, recalculated to 100% fluid-free basis. About 20 individual glass shards or points were analysed for each sample.

<table>
<thead>
<tr>
<th></th>
<th>LSM tephra</th>
<th>Guaje</th>
<th>Tsankawi</th>
<th>Tsankawi</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>77.16</td>
<td>76.64</td>
<td>76.81</td>
<td>77.32</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12.21</td>
<td>12.49</td>
<td>12.18</td>
<td>11.43</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.49</td>
<td>1.45</td>
<td>1.60</td>
<td>1.64</td>
</tr>
<tr>
<td>MgO</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.06</td>
<td>0.06</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>CaO</td>
<td>0.27</td>
<td>0.28</td>
<td>0.28</td>
<td>0.27</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.37</td>
<td>4.49</td>
<td>4.66</td>
<td>4.64</td>
</tr>
<tr>
<td>K₂O</td>
<td>4.35</td>
<td>4.52</td>
<td>4.36</td>
<td>4.59</td>
</tr>
<tr>
<td>similarity coefficient</td>
<td>–</td>
<td>0.9740</td>
<td>0.9707</td>
<td>0.9554</td>
</tr>
</tbody>
</table>

In the field and under the microscope, the tephra layer shows only a slight indication of weathering; in its core there is no such indication at all (Fig. 4). This preservation would be unlikely if the tephra layer had been as close to the surface since 1.65 Ma as it is now. Thus, the question arises whether material originally overlying the LSM tephra layer has been eroded or whether the tephra layer, despite its pure appearance, was reworked considerably after it had been originally deposited and is in a secondary position in this profile. The present contribution discusses evidence for the latter hypothesis, along with consequences for tephrochronology in steep relief.

2. Methods

Particle sizes were determined by sieving and the pipette method, using Na₄P₂O₇ as a dispersant, after removing carbonate by treatment with acetic acid. However, in the following discussion of the texture will be restricted to the fine-sand particle-size class (0.063–0.2 mm), which is indicative of the LSM tephra layer. The carbonate content was determined with a gas-volumetric Scheibler apparatus (Page et al., 1982).
Fig. 3. Exposure under study in the La Sal Mountains.

Fig. 4. La Sal Mountains Tephra layer as exposed in the right part of the profile.

Fig. 5. Sketch of soils and deposits of the exposure under study. The scale is approximate. Circles indicate samplings; filled circles indicate the presence of glass shards. Carbonate concentrations are <10% (Bt horizons), 10–50% (Btk) and >50% (Bk) of the fine earth fraction. There is no visible soil development in the tephra layers and in the gully fill. In the stone lines Btk horizons are present.
Light minerals were microscopically counted on a representative fraction of the whole sample. For heavy-mineral analysis, heavy particles of the 100–200 µm size fraction, separated by floatation in bromoform, were embedded in resin (refraction index 1.67) for microscopic examination (cf. Marcinkowski & Mycielska-Dowgiałło, 2013). Approximately 200 non-opaque grains were identified per sample.

### 3. Results and discussion

Where the LSM tephra layer was found, the exposure consists of several soil horizons that were formed mainly from loess-dominated slope deposits during various soil-forming episodes (Fig. 5). Various palaeosols can be distinguished by means of their compound clay- and carbonate-enriched (argillic and calcic, respectively) horizons: the carbonate in these compound horizons must have accumulated after the argillic properties had been formed, because carbonate enrichment and clay illuviation cannot occur simultaneously in the same horizon, and clay translocation is only possible during or after the carbonate has been depleted (see Kleber, 2000, for detailed reasoning). Furthermore, a much warmer soil-temperature regime than the area is experiencing now would have been needed to form calcic horizons reaching as deep as in this profile, and clay translocation is only possible during or after the carbonate has been depleted (see Kleber, 2000, for detailed reasoning).

#### Table 2. Selected properties of the LSM Tephra (1) and of some samples (2–5).

<table>
<thead>
<tr>
<th>Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>heavy mineral (% of transparent grains)</td>
<td>74.1</td>
<td>44.2</td>
<td>47.5</td>
<td>35.7</td>
<td>16.1</td>
</tr>
<tr>
<td>clinopyroxene</td>
<td>9.9</td>
<td>17.9</td>
<td>18.8</td>
<td>28.6</td>
<td>61.1</td>
</tr>
<tr>
<td>green calcic amphibole</td>
<td>8.8</td>
<td>3.8</td>
<td>4.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>hypersthene</td>
<td>5.0</td>
<td>30.5</td>
<td>27.0</td>
<td>33.3</td>
<td>22.2</td>
</tr>
<tr>
<td>titanite</td>
<td>2.2</td>
<td>3.6</td>
<td>2.5</td>
<td>2.4</td>
<td>0.6</td>
</tr>
<tr>
<td>fine sand (% of fine earth)</td>
<td>54.7</td>
<td>36.0</td>
<td>34.9</td>
<td>22.0</td>
<td>16.4</td>
</tr>
<tr>
<td>glass shards (% of light grains)</td>
<td>95</td>
<td>80</td>
<td>80</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

See Figure 3 for the position of the selected samples in the profile. Analyst R. Schill, Geomorphology Laboratory, Bayreuth University.

The LSM tephra layer is also essentially absent in other samples from this area: orthopyroxene with the petrographic appearance of hypersthene (Kleber, 1992, and unpublished analyses). Among the light minerals are many glass shards. The grain-size distribution of the tephra particles peaks in the fine-sand fraction, whereas the surrounding slope deposits largely contain coarse silt. Two other samples (# 2 and # 3) also contain conspicuous amounts of glass shards, fine sand, and clinopyroxene, as well as some orthopyroxene. Sample # 2 stems from approximately the same stratigraphic position as sample # 1 but is more contaminated with surrounding loessic material, whereas sample # 3 stems from a small sand lens within soil 4. Sample # 4 is from the same soil and contains some tephra constituents, i.e. glass shards, visible in the field aided by a magnifying glass. Sample # 5 is from soil 5 and is free of tephra material.

Glass shards occur in various layers (Fig. 5) down to and including the parent material of soil 4, whereas they were found to be absent beneath soil 4. Contrary to other textural classes and minerals (not shown), there are significant correlations among the tephra constituents: glass shards, clinopyroxene, and fine sand (Fig. 6). Increases in one component are accompanied by significant proportional increases in the others in the entirety of samples. This is in-

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*Heavy-mineral analysis as a tool in tephrochronology, with an example from the La Sal Mountains, Utah, U.S.A.*
interpreted as indicating that these components have one major source in common. Presumably, a layer of the Guaje tephra has yielded particles from upslope since the time of the formation of the parent material of soil 4 already, and became finally eroded and reworked when the parent material of soil 2 was deposited. Up-slope from the exposure, the loess-rich slope deposits wedge out within a few metres, and no occurrence of a first-deposition tephra layer could be found, which is, therefore, assumed to have been eroded completely.

Gelifluction could account for this en-bloc reworking, as it is able to dislocate matter without mixing it with neighbouring materials:

1. The tephra material may have been transported as a frozen block. Due to its porous structure, the thawing behaviour of frozen tephra likely differs remarkably from surrounding materials. Though gelification usually dislocates thawed material above the underlying frozen substrate (French, 2007), delayed thawing of tephra material relative to its surroundings (similar to strongly weathered rock fragments dislocated undisturbed by gelification as described by Kleber, 1997) may have resulted in dislocation affecting it as a still frozen block embedded in unfrozen matter.

2. Alternatively, gelification might have been laminar. Laminar dislocation also does not mix neighbouring materials (Jaesche et al., 2003), and there is evidence that it is frequent in gelification sediments (Kleber et al., 2013). However, at its lateral edges the tephra layer is well mixed with other materials, as depicted with sample #2 in Table 2.

4. Conclusions

The tephra constituents down to soil 4 indicate that tephra material was admixed to the parent material of soil 4, i.e. significantly earlier than the pure tephra layer embedded into soil 2 was formed. This suggests that tephra material may be reworked quite a long time after its primary deposition, nevertheless retaining an essentially pure character. Thus, age determinations based solely on a pure tephra layer may yield incorrect results due to non-apparent reworking of tephra material. Heavy-mineral analyses may yield evidence of tephra constituents throughout a profile, and may allow to fathoming a reworking history.

Therefore, it is necessary to interpret tephra layers – even if they appear pure and uncontaminated with surrounding material – with
great care, similarly to other relative-dating methods. This certainly holds true for tephra layers preserved in steep relief, as demonstrated in this study; but it has to be tested whether similar caveats may apply to low slope angles as well, because slope dynamics able to transport such material frozen or by laminar gelification may act on essentially any slope regardless of its inclination (French, 2007).

Acknowledgements

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