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Late-Holocene land surface change in a coupled social–ecological system, southern Iceland: a cross-scale tephrochronology approach

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ABSTRACT

The chronological challenge of cross-scale analysis within coupled socio-ecological systems can be met with tephrochronology based on numerous well-dated tephra layers. We illustrate this with an enhanced chronology from Skaftártunga, south Iceland that is based on 200 stratigraphic profiles and 2635 individual tephra deposits from 23 different eruptions within the last 1140 years. We present new sediment-accumulation rate based dating of tephra layers from Grímsvötn in AD 1432 ± 5 and AD 1457 ± 5. These and other tephras underpin an analysis of land surface stability across multiple scales. The aggregate regional sediment accumulation records suggest a relatively slow rate of land surface change which can be explained by climate and land use change over the period of human occupation of the island (after AD ~870), but the spatial patterning of change shows that it is more complex, with landscape scale hysteresis and path dependency making the relationship between climate and land surface instability contingent. An alternative steady state of much higher rates of sediment accumulation is seen in areas below 300 m asl after AD ~870 despite large variations in climate, with two phases of increased erosion, one related to vegetation change (AD 870–1206) and another related to climate (AD 1597–1918). In areas above 300 m asl there is a short lived increase in erosion and related deposition after settlement (AD ~870–935) and then relatively little additional change to present. Spatial correlation between rates of sediment accumulation at different profiles decreases rapidly after AD ~935 from ~4 km to less than 250 m as the landscape becomes more heterogeneous. These new insights are only possible using high-resolution tephrochronology applied spatially across a landscape, an approach that can be applied to the large areas of the Earth's surface affected by the repeated fallout of cm-scale tephra layers.

1. Introduction

The long-term perspectives of Quaternary science offer much to the contemporary debates about landscape resilience and the drivers of land surface change (Dearing et al., 2010). Recent decades have seen significant progress in both the production of diverse proxy records of environmental change and the development of high-resolution, long-term time series (Dansgaard et al., 1993; Brauer et al., 1999; Bonnefille and Chalie, 2000; Wang et al., 2001; Marlon et al., 2008). High quality archives can now provide data with the sub-decadal, annual or seasonal resolution needed for the analysis of land surface changes on human timescales and assessments of possible interactions between environmental change and human societies (e.g., Dearing, 2008). However, while many fundamental challenges of temporal resolution have been tackled (Lowe et al., 2008; Ramsey, 2008), key issues of spatial resolution remain unsolved.

Land surface change can be driven at multiple scales. These can be both 'top-down' (as in the case of global scale processes that drive climate changes with local impacts) and 'bottom-up' (as in the case of small scale land use changes that in aggregate have regional effects). Precise and accurate chronologies applicable across a nested sequence of scales are necessary in order to make effective connections between global hypotheses, regional narratives and the detail of individual sites. The spatial and chronological challenges presented by the cross-scale analysis of land surfaces can be met with high-resolution tephrochronology which can define spatial patterns across scales from millimetres to hundreds of kilometres (Dugmore et al., 2009; Lowe, 2011; Streeter et al., 2012).

This approach can also be used to test how resilient the land surface has been to anthropogenic disturbance and climatic influences over millennial timescales. Resilient systems can tolerate a

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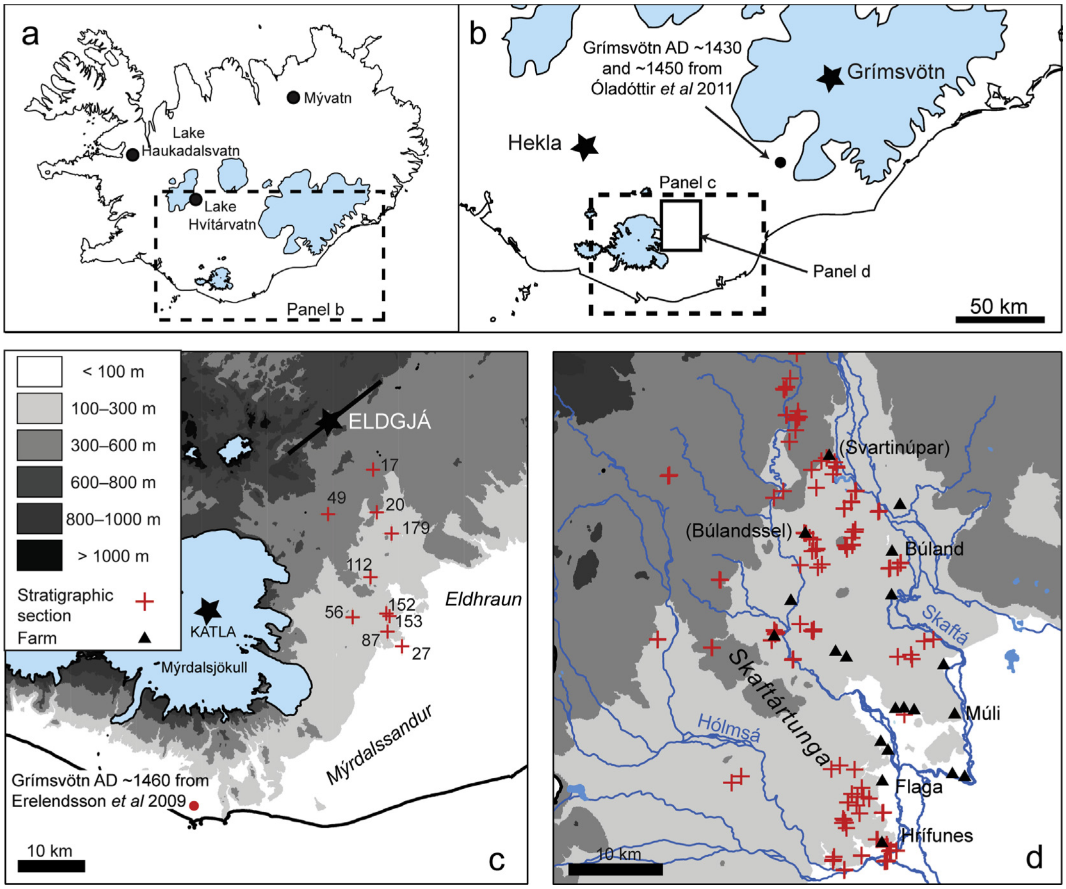

Fig. 1. Study area. Overview location (a) with location of proxy records in Figs. 8 and 9. Location of Grímsvötn (b) and section with Grímsvötn layers described in this paper. Location of sampled tephras (c), stratigraphic section numbers correspond to those in SI. Table I. Profiles 153 and 179 were used to calculate ages for the two undated Grímsvötn tephras (Fig. 4). (d) Location of stratigraphic sections with major rivers and landholdings also shown. Farms in parenthesis are abandoned. Pre-settlement woodland is generally found at less than 300 m asl (Thórhallsdóttir, 1997): extent of woodland cover on sandur unknown prior to settlement.

wide range of conditions and are likely to remain in a similar state through time (Scheffer et al., 2009). In contrast systems with low resilience are sensitive to changes in conditions and are likely to change state over time (c.f. Bhagwat et al., 2012). Changing resilience may explain why some perturbations produce large changes when earlier perturbations of similar magnitude produced little change (Scheffer et al., 2009). As resilience is scale dependent, effective resilience thinking requires engagement at the scale of enquiry, a scale above and a scale below (Walker et al., 2004). Enhanced resilience at one scale within a landscape may be directly related to reduced resilience at another scale. Within coupled social–ecological systems (SES) the relevant scales of enquiry are likely to be related to the scales of human use of the landscape (e.g., field systems, landholdings, community management of resources, regional networks of exchange).

In this paper we develop tephrochronology for the cross-scale analysis of land surface change. Tephra layers provide a limited number of discrete dates within a time series of data because of the episodic nature of volcanic eruptions, but tephrochronology provides unparallelled scope for precise and accurate 3-D reconstructions of change related to the isochrons formed by tephra layers. This approach offers a hitherto largely untapped potential to develop understanding of the coupled interactions of environments and people, particularly those expressed as changing patterns of land surface change.

We focus on methodological issues of precision, accuracy, data density and statistical analysis related to the development of regional tephrochronology for multi-scale studies of land surface change over millennial timescales. We maximise the resolution of tephrochronology in Iceland by identifying patchy and marginal tephra layers and using high-resolution measures of sediment accumulation to provide calendrical dates. We use the example of landscape degradation to assess change at different spatial and temporal scales within a coupled SES and to address questions of long-term resilience of a land surface to changes in climate and vegetation cover.

2. Regional setting

In order to develop new perspectives we focus on southern Iceland, one of the best locations in the world for applications of tephrochronology (Fig. 1), where changes in SESs and climate are expressed in land surface changes. Iceland is important for understanding the human impact on the environment because it was settled in comparatively recent historical times and so can provide accessible pre-human baselines. In addition the existence of the Landnám tephra (deposited 871 ± AD, Grönvold et al., 1995), which dates from immediately prior to Norse settlement, marks a precisely defined change from a purely ecological system to a combined social–ecological system.

The area east of Mýrdalsjökull includes the areas of Skaftártunga, Mýrdalssandur, Eldhraun and Alftaversafrettur and extends from the southern coastal sandur of Iceland to the interior highlands (Fig. 1a). The sandur plains to the south of the study area have