

ELECTRICAL RESISTIVITY STRUCTURE OF A RAISED MIRE: MALHAM TARN MOSS, YORKSHIRE DALES, UK.

NEIL C. MITCHELL AND STEPHEN BOULT

School of Earth and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL

Malham Tarn Moss is a raised mire that has grown over an impermeable layer such that the shape of its water surface represents near equilibrium between accumulating rainwater and lateral drainage within the mire. With a view to seeing how the water conductivity varies within the mire accompanying this drainage pattern and whether a uniform impermeable layer likely underlies the mire, an electrical resistivity survey was carried out in 2013. The survey involved deploying a 64-electrode system along a single 315-m north-south profile adjacent to a line of samples collected in boreholes in the 1960s. The derived resistivity values decrease from $>200 \Omega\text{m}$ at the mire surface (attributed to rainwater) down to $<50 \Omega\text{m}$ at 10 m depth below the surface, which borehole and other geophysical data suggests is within glacial till underlying the mire. This low value would be consistent with the presence of clay minerals such as occur in glacial till and/or the presence of high solute concentrations from water reactions with rocks. The resistivity minimum varies by only $10 \Omega\text{m}$ laterally, suggesting a uniform composition of the sealing basal layer. Below 30 m depth, where resistivities are $>1000 \Omega\text{m}$, which likely represent underlying bedrock, a lateral resistivity boundary suggests a deeper geological boundary that has not previously been recorded. Within the mire, the resistivity structure is laterally uniform, with 100 and $200 \Omega\text{m}$ contours rising towards the northern edge of the mire by only ~ 1 m relative to the surface. This is surprising if the hydraulic structure were to involve internal flow balancing rainwater input in a uniform-permeability structure and if low resistivities originate from diffusion of solutes entering the mire from below. We suggest that this observation can probably be explained by non-uniform permeability, with most lateral drainage occurring near the mire surface.

INTRODUCTION

Raised mires or peat bogs are low-relief mounds of moss and other organic matter, typically found in cold, wet climates where evaporation is limited. The water table within such mires has a rounded semi-elliptical shape in profile that reflects a balance between rainfall from above and internal drainage. The water table steepens towards the edges because a greater lateral hydraulic pressure gradient is required to balance the cumulative discharge from rain falling 'upstream' towards the mire centre. Where moss grows significantly above the water table, the moss can dry out in summer and become eroded, so the moss tends to track the water table in mature mires.

Figure 1 shows a predicted mire shape in profile according to a simple hydraulic model of Ingram (1982), which predicts mire surface topography relative to elevation of the mire edges H (m):

$$H = \left(\frac{U}{K}\right)^{1/2} (2Lx - x^2)^{1/2} \quad (1)$$

where U represents recharge (rainfall with units m s^{-1} ; equivalent to water discharge at the mire edge in $\text{m}^2 \text{s}^{-1}$ divided by L), x is distance from the mire edge (m), L is half the width of the mire (m) and K is hydraulic conductivity (m s^{-1}). The mire shape in profile predicted by equation (1) is shown in Figure 1 (note ordinate x increases to the left). In constructing this model, it was assumed that the mire has grown so that its shape represents a balance between rainwater entering its upper surface and slow drainage of water internally through the moss, while drainage into or from the underlying till and rocks is insignificant, as is evaporation loss. Although equation (1) only represents the effect of drainage in one dimension, Ingram (1982) showed that it accurately represented the topography of Dunn Moss in east Perthshire. In our own work with traditional surveying methods, we have also found it matches the profile shape of Malham Tarn Moss. In practice, the equivalent equation to (1) for a circular mound of radius L is functionally very similar, differing only by a constant factor $1/\sqrt{2}$ (Clymo 1984).

Geophysical methods offer information that is complementary to direct sample collection, while providing more continuous and widespread data, overcoming some under-sampling issues. Although peat structures have been studied extensively with geophysical methods in the past, there has been less work carried out on raised mires as far as we are aware, in particular with electrical resistivity surveying (otherwise known as geophysical resistivity tomography) as used here. We have found limited examples of published resistivity work on raised mires in Finland (Puranen *et al.* 1999) and in the Alps (Sass *et al.* 2010), which we discuss later. Much of the existing work has been carried out with ground penetrating radar (GPR). Although GPR data can be collected more efficiently and can reveal

greater structural detail, resistivity surveying can provide deeper images of the subsurface (potentially imaging structure underlying mires) and quantitative estimates of the bulk material resistivity structure. Resistivity (units of Ωm) is simply a scale-normalized measure of material resistance and is inversely related to conductivity (units of S m^{-1}), so the resistivity results can be compared with measurements of, for example, water conductivity (e.g., $100 \Omega\text{m}$ is equivalent to 0.01 S m^{-1}).

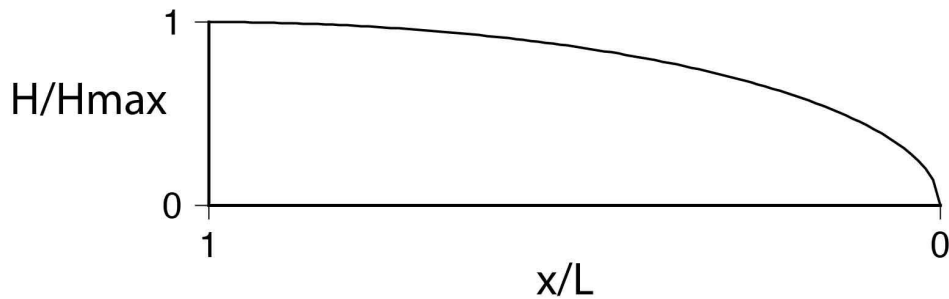


FIGURE 1. Relief profile of a mire according to the theoretical model of Ingram (1982). Ordinate x is shown increasing to the left to be compatible with Figure 4a ($x/L=1$ is centre of mire and $x/L=0$ is its edge).



FIGURE 2. Map of Malham Tarn Moss and Malham Tarn (from Google Earth, reproduced under the terms of their Copyright).

Malham Tarn Moss comprises a series of raised mires over a distance ~ 700 m across lying on the west side of Malham Tarn, North Yorkshire (Fig. 2) at an altitude of 375–380 m above sea level. According to O'Connor (1964), the tarn is underlain by Silurian shales and other clastic rocks. Low permeabilities of those strata and/or glacial till overlying them may explain the existence of the Tarn here; surface water does not commonly remain on the surrounding more permeable limestone. The exact nature of the base of the mire seems only constrained by limited samplings by boreholes reported by Pigott and Pigott (1963), whose figures show glacial till underlying the mire around its edges. Field observations revealed that glacial till clearly lies near the surface under Spiggot Hill (Fig. 2).

The mire has been surveyed with GPR by Dinsdale Moorland Services Ltd and those results disclosed to us in the form of an unpublished report (Peter Welsh, National Trust, pers. comm.). Most of the other work on the mire has concerned its flora (Adam *et al.*, 1975; Cooper and Proctor, 1998), water chemistry (Proctor, 1994; Proctor, 2003) and palaeoclimate (Turner *et al.*, 2014). Proctor (2003) found that water on the mire surface had low ionic concentrations very close to those of rainwater. He suggested that minor variations could be explained by evaporation and ion exchange. Further details on the mire and local climate are given by Adam *et al.* (1975).

As few resistivity surveys of raised mires have been carried out, we hope this report will contribute to the present knowledge of these features, in particular, of their internal water structures. As we discuss later, the patterns of resistivity at Malham Tarn Moss do not obviously represent uniform drainage of the mire, perhaps indicating a more surficial drainage. A further advantage of deep resistivity imaging is in helping to understand the structure underlying the mire. The geological boundary between shale and limestone that O'Connor (1964) drew along the north side of Malham Tarn and the mire is not well constrained locally as there are few *in situ* rock outcrops. Furthermore, although surface water from the limestone to the north of the mire is probably largely captured by the small stream there (Cow Beck; Fig. 2), the extent of groundwater input to the mire is unknown, an issue that could potentially be informed by resistivity surveying.

METHOD

Resistivity profile data were collected on 17 April 2013 with a 64-electrode Tigre system of Allied Associates Ltd using a Wenner array configuration. The full survey line of 315 m is located in Figure 2 over an aerial photograph of the area. The field data were inverted using software RES2DINV (Loke and Barker, 1996) to produce the resistivity profile shown in Figure 3. In the following, we interpret broad-scale variations of these data. Fine variations in contours may be artefacts of the inversion (e.g., arising from some weaker electrode contacts) and curvature of contours within 10 m of the edges of the inversion result may also be an artefact resulting from poor data constraints. A weak electrode contact is probably responsible for the large resistivity value at the surface at 280 m profile distance. The inversion results are shown alongside the borehole sample interpretations of Pigott and Pigott (1963) in Figure 4 and two vertical sections through the inversion results are shown in Figure 5.

RESULTS AND INTERPRETATION

The data show a surface layer ~2-3 m thick with resistivities greater than 200 Ωm . These moderately high resistivities are interpreted as due to rainwater and roughly correspond with the surface layer in the Pigott and Pigott (1963) interpretation in Figure 4a, although that is thinner. The increasing resistivity with depth within the mire is likely produced by molecular diffusion of solute from the underlying groundwaters or from chemical reactions with rocks below the mire. A discrete groundwater source seems to be ruled out by these data, given the nearly uniform resistivities along the mire.

A minimum of ~50 Ωm occurs at ~15 m depth. Detailed comparison with the profile of Pigott and Pigott (1963) in Figure 4a and with the interpreted depth of the peat layer in the GPR study (green line in Figure 4b) suggests that this minimum resistivity lies within the boulder clay underlying the mire. Resistivities similar to 50 Ωm have been recorded by other studies on glacial till, although till resistivities can vary (e.g., Cuthbert *et al.*, 2009; Pellicer and Gibson, 2011; Sass *et al.*, 2010). No particular resistivity boundary marking the base of the mire was observed, rather resistivity decreases smoothly going downwards to the minimum (Fig. 5). In the enlarged version of the data (Fig. 4b) and in the graph in Figure 3b, the centre of this minimum varies in resistivity laterally by only 10 Ωm , suggesting uniform composition of the boulder clay (uniform clay content and/or solute concentration of pore waters).

Below this minimum, resistivity steadily increases to more than 1000 Ωm below 30 m depth, typical of water-saturated rocks (Telford *et al.*, 1976). North of 170 m along the profile, a small area of resistivity as low as ~800 Ωm was imaged at the base of the profile. Although the inversion results are potentially affected by poor electrical contacts, the field data all show lower apparent resistivities here so this seems likely to be a true feature. According to the geological map of O'Connor (1964), the roughly east-west running boundary between the Silurian rocks and Carboniferous rocks (which are mostly limestone here) lies to the north at about the latitude of the stream (Cow Beck) shown in Figure 2. Our boundary would lie ~100 m further south. More porous structures of limestone may explain the transition below 30 m depth to less resistive rocks at 170 m profile distance. Alternatively, a boundary within the shale may explain it, e.g., from solute-filled fracture porosity.

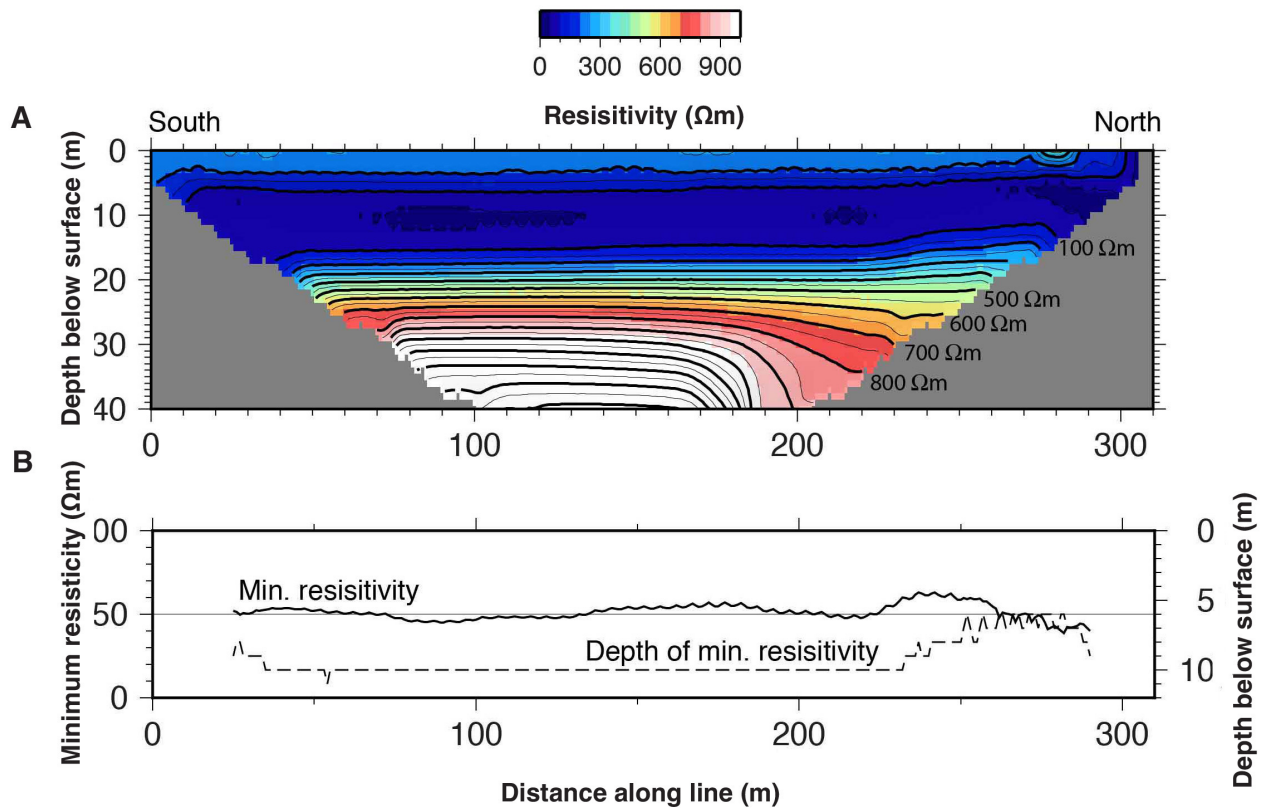


FIGURE 3. (a) Resistivity profile shown at 2:1 vertical exaggeration (contour interval is 50 Ωm with every 100 Ωm in bold). Profile is located in Figure 2. (b) Minimum resistivity value (continuous line) and depth below surface of that minimum (dashed line). (Values affected by edge effects at ends of lines are omitted.)

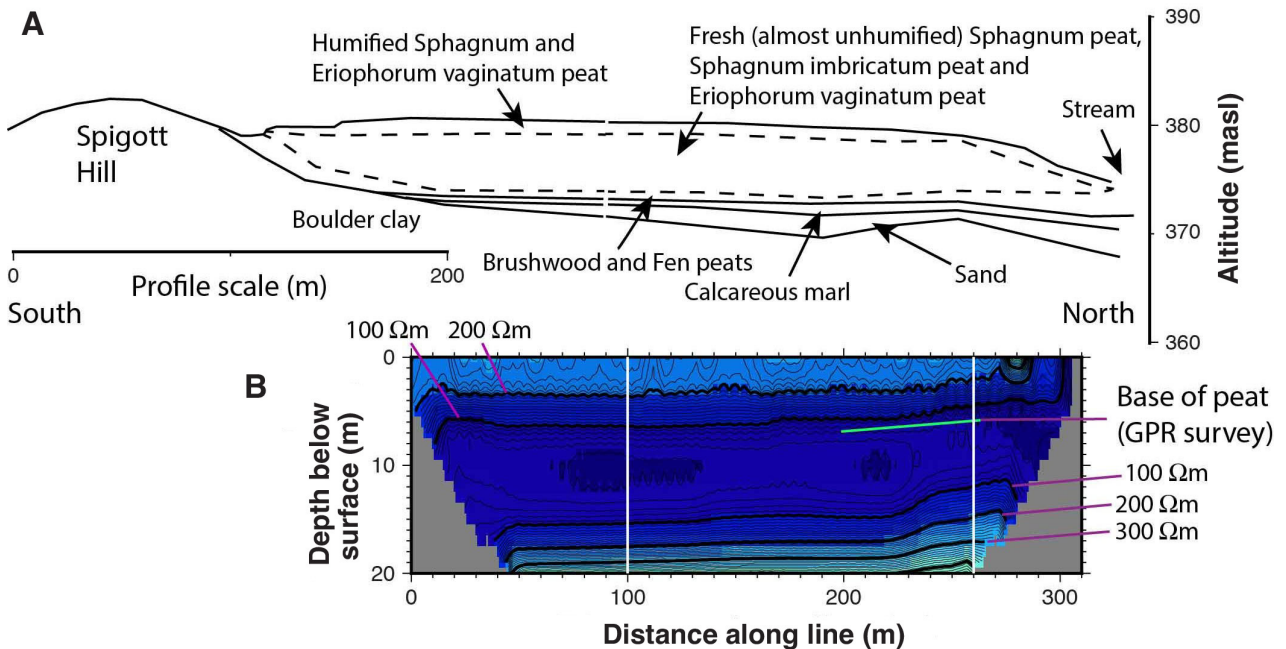


FIGURE 4. Comparison of (a) profile derived from interpreting borehole samples in the early 1960s (adapted from Pigott and Pigott (1963)) and (b) the 2013 electrical resistivity measurements. Profiles are located in Figure 2. The profiles are shown at the same scale and 5:1 vertical exaggeration. Contour interval in (b) is every 10 Ωm and colour intervals correspond with the intervals in Figure 3. Two white vertical lines locate the two resistivity vertical profiles in Figure 5.

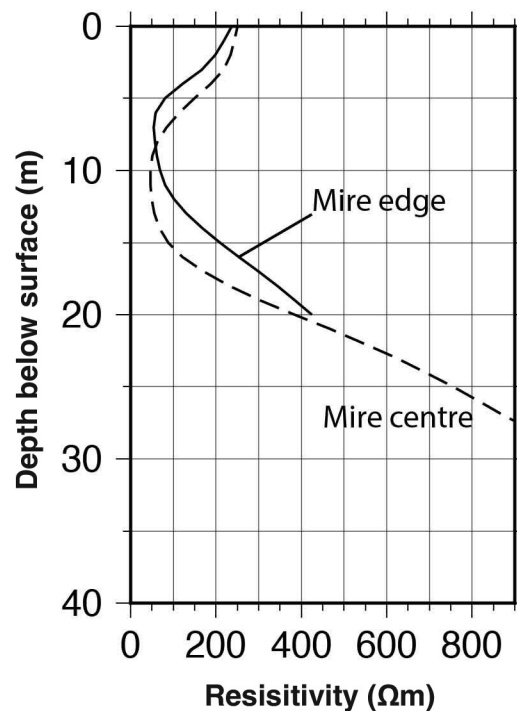


FIGURE 5. Vertical profiles of resistivity at 100 m distance ("Mire centre") and 260 m distance ("Mire edge") along the survey line, located by the white vertical bars in Figure 4b.

DISCUSSION

Sass *et al.* (2010) showed resistivity profiles across two Alpine mires. Their results similarly show resistivity decreasing from the surface downwards, from ~300 Ωm to <100 Ωm at the mire base. Their near-surface resistivity values varied strongly across the mires by >100 Ωm . These mires were much smaller (<100 m across) than Malham Tarn Moss. A larger (almost 2 km across) raised mire in Finland was studied by taking repeated electrical resistivity measurements using a short 4.5 cm electrode array attached to a probe (Puranen *et al.* 1999). The measurements also revealed a laterally heterogeneous structure, though with resistivity systematically decreasing by greater than a factor of two towards the mire base, somewhat similar to here, with resistivities reaching 50 Ωm .

If resistivity variations within the mire represent the accumulated effects on solute content of the aqueous fluid from molecular diffusion from rocks (e.g., limestone) in the till beneath the mire, it is surprising that there is only a modest change in resistivity structure towards the mire margin in the north. A similar lack of a major change in resistivity structure at mire margins was found in the other two resistivity studies (Puranen *et al.* 1999; Sass *et al.* 2010). The pressure gradient within the mire driving sub-surface flow is proportional to the hydraulic head gradient ($\partial H/\partial x$), which can be expected based on the surface topography to increase rapidly towards the mire edges (Figs 1 and 4). As pressure gradient is uniform with depth at any point along the profiles, there would be equally rapid movement of upper and lower mire waters if permeability were uniform. A parcel of water near to the base should progressively migrate laterally, becoming more concentrated with the accumulated effect of diffusion from rocks below, leading to smaller resistivities, but the effect is surprisingly minor (Fig. 5).

We suspect that the drainage of the mire involves flow mainly near its surface, so that it involves 'young' rainwater that has not become strongly affected by diffusion from below. Differing conclusions over whether mires typically have uniform or strongly varied permeability structures are represented in the literature. Morris and Waddington (2011) outlined some evidence showing that permeability of peats can decrease strongly non-linearly with depth and modelled the effect of an exponentially decreasing permeability with depth. Their results for the centre of a peat mound showed how the half-life of an introduced tracer would likely increase dramatically with depth, consistent with developing low resistivity as found here. Future work may usefully attempt dating of internal water samples using radiometric methods to address this issue.

CONCLUSION

An electrical resistivity profile collected across Malham Tarn Moss has imaged its structure down to below 40 m. The results reveal resistivities typical of bedrock below ~20 m depth, over which lies a layer of glacial till of uniform resistivity, implying a uniform composition. A boundary part way along the profile in the deeper section suggests a geological boundary. Within the mire itself, resistivity is >200 Ωm at the surface (corresponding with rainwater) and decreases smoothly with depth associated with diffusion of solutes from the underlying till. The remarkable uniformity of this structure along the profile suggests that there are no discrete locations of groundwater ingress. We were surprised to find only modest change in resistivity structure towards the mire edge. This may indicate that permeability decreases with depth so that most lateral drainage occurs preferentially near the mire surface.

ACKNOWLEDGEMENTS

We thank the National Trust for permission to carry out this work. The resistivity equipment was funded by the University of Manchester and data were collected with the help of the Environmental Science BSc class of 2013. We thank also the staff of the Malham Tarn Field Centre for their hospitality during our stays, all of which have been enjoyable. Figures in this article were created with the "GMT" software system (Wessel and Smith 1991).

REFERENCES

- Adam, P., Birks, H.J.B., Huntley, B., Prentice, I.C. (1975). Phytosociological Studies at Malham Tarn Moss and Fen, Yorkshire, England. *Vegetatio*, **30**, 117-132.
- Clymo, R.S. (1984). Limits to peat bog growth. *Philosophical Transactions of the Royal Society*, **303**, 605-654.
- Cooper, E.A., Proctor, M.C.F. (1998). Malham Tarn National Nature Reserve: Malham Tarn Moss and fens. *Field Studies*, **9**, 277-312.
- Cuthbert, M.O., Mackay, R., Tellam, J.H., Barker, R.D. (2009). The use of electrical resistivity tomography in deriving local-scale models of recharge through superficial deposits. *Quat. J. Eng. Geol. Hydrogeol.*, **42**, 199-209.
- Ingram, H.A.P. (1982). Size and shape in raised mire ecosystems: a geophysical model. *Nature*, **297**, 300-303.
- Loke, M.H., Barker, R.D. (1996). Rapid least squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophysical Prospecting*, **44**, 131-152.
- Morris, P.J., Waddington, J.M. (2011). Groundwater residence time distributions in peatlands: Implications for peat decomposition and accumulation. *Water Resour. Res.* **47**, article W02511, doi:02510.01029/02010WR009492.
- O'Connor, J. (1964). The geology of the area around Malham Tarn, Yorkshire. *Field Studies*, **2**, 53-82.
- Pellicer, X.M., Gibson, P. (2011). Electrical resistivity and Ground Penetrating Radar for the characterisation of the internal architecture of Quaternary sediments in the Midlands of Ireland. *J. Applied Geophysics*, **75**, 638-647.
- Pigott, C.D., Pigott, M.E. (1963). Late-glacial and post-glacial deposits at Malham, Yorkshire. *New Phytologist*, **62**, 317-334.
- Proctor, M.C.F. (1994). Seasonal and shorter-term changes in surface-water chemistry on four English ombrogenous bogs. *Journal of Ecology*, **82**, 597-610.
- Proctor, M.C.F. (2003). Malham Tarn Moss: the surface-water chemistry of an ombrotrophic bog. *Field Studies*, **10**, 553-578.
- Puranen, R., Mäkilä, M., Säävuori, H. (1999). Electric conductivity and temperature variations within a raised bog in Finland: implications for bog development. *The Holocene*, **9**, 13-24.
- Sass, O., Friedmann, A., Haselwanter, G., Wetzel, K.-F. (2010). Investigating thickness and internal structure of alpine mires using conventional and geophysical techniques. *Catena*, **80**, 195-203.
- Telford, W.M., Geldart, L.P., Sheriff, R.E., Keys, D.A. (1976). *Applied Geophysics*, Cambridge University Press, New York, 860pp.
- Turner, T.E., Swindles, G.T., Roucoux, K.H. (2014). Late Holocene ecohydrological and carbon dynamics of a UK raised bog: impact of human activity and climate change. *Quaternary Science Review.*, **84**, 65-85.
- Wessel, P., Smith, W.H.F. (1991). Free software helps map and display data. *Eos, Transactions, American Geophysical Union*, **72**, 441.