DISTRIBUTION AND SUBSURFACE STRUCTURE OF BEAVER IMPACTED PEATLANDS IN THE ROCKY MOUNTAINS

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Alasdair David Morrison

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ABSTRACT

Peatlands provide a variety of ecosystem services including carbon sequestration, nutrient cycling and increased biodiversity, and are thus an important Canadian natural resource. Mountain peatlands, including those in the foothill region of the Canadian Rockies are particularly important due to their proximity to headwater streams which supply the Prairie Provinces with water. Yet, distribution of peatlands in the Canadian Rocky Mountains is unknown. There is also a lack of understanding of the form of these peatlands and the processes influencing them. The purpose of this research is to improve our understanding of Canadian mountain peatlands in terms of their abundance, distribution and subsurface form. Specific objectives are to: determine the distribution of beaver impacted wetlands in the study area; quantify the proportion of these which are peatlands; determine the impact beaver have on one hydrological variable, the area of open water and; describe the stratigraphy of peatlands with beaver at their surface. Beaver impacted wetland distribution was assessed through manual analysis of georeferenced aerial photographs. Combining these data with an existing GIS layer provided the basis of a wetland inventory of the region, allowing wetlands to be separately inventoried by physiographic location (Mountain and Foothills) and jurisdiction (Alberta Parks, Municipal Districts, Improvement Districts and First Nations Reserve). Approximately 75% of wetlands are located in the Foothills and Municipal District areas. Beaver impact is evident in 30% of the 529 wetlands inventoried, with the highest number in protected areas. Area of open water on wetlands, as assessed by manual analysis of aerial photographs, indicated that beaver impacted sites have on average approximately ten times more open surface water area than non-beaver impacted sites. In total, 81 wetlands were ground-truthed of which 77% were peat-forming wetlands or peatlands. Ground penetrating radar surveys and soil coring performed at 9 peatlands with beaver activity at their surface showed structural differences from those peatlands for which ecosystem services are described in the literature in that they are stratigraphically complex. Little is known about the factors affecting how this form develops, and this requires further study. The distribution of peatlands in the study area highlights them as important landscape units, and that in order to best manage them, further research is required into the various influences on their hydrological and ecological function.

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1. INTRODUCTION

Wetlands are a globally important landscape feature providing a wide variety of ecosystem services (Stein et al., 2004; Greb et al., 2006). There is an estimated 12.8 million km^2 of wetlands worldwide, although this figure is unreliable as accurate national inventories are not available everywhere (Finlayson et al., 1999). Despite their relatively small aerial extent relative to other landscape units, wetlands provide important habitat for unique flora and fauna (Greb et al., 2006). They are often referred to as biogeochemical hotspots (McClain et al., 2003) and provide ecosystem services such as water storage (Stein et al., 2004). These services are beneficial to both the environment and human society, as they promote biodiversity, provide zones for natural removal of pollutants from water and provide a hydrological buffer that can mitigate flooding during high rainfall events (Hey and Philippi, 1995) and drought during periods of low rainfall (Hood and Bayley, 2008). Understanding the distribution and function of individual wetlands on a landscape and how these affect the services they provide to a watershed is vitally important in managing these features.

Peatlands are a particularly important form of wetland because, in addition to providing the ecosystem services associated with wetlands in general, they represent a major carbon sink, affecting global climate. Although peatlands only make up 3% of world soil, they store 33% of the global carbon pool (Charman, 2002). Peatlands in Canada account for approximately 14% of the global total (Warner, 2005). A number of studies have investigated the form and function of Canadian peatlands (Reeve et al., 2000; Wieder and Vitt, 2006; Ise et al., 2008), but these works have largely ignored those occurring in mountainous regions. There has been some study of peatlands in the Rocky Mountains in the Northern United States (e.g., Chadde et al., 1998). Given the similar physiographic setting, peatlands are likely to be present in similar numbers in the Canadian Rockies and as such are likely to be of great importance in these watersheds (Stein et al., 2004).

Peatlands in the Canadian Rocky Mountains can be inhabited by beaver (Janzen and Westbrook, 2011). Beaver are a known ecological engineer, shown to impact the vegetation, surface and subsurface hydrology and biogeochemistry and areas they inhabit (Naiman et al., 1988; Butler and Malanson, 1995; Westbrook et al., 2006), but the influence of beaver on peatland form and function has been poorly described. The term, “peatland form” relates to the structure of the peat soil, and how this has come about. It has been shown that the subsurface structure varies in other peatlands as a result of external environmental factors (Charman, 1995; Loisel 2013), but the structures of mountain peatlands have not been widely studied. As an important national and regional natural resource, peatlands need to be managed appropriately. To do this effectively, a better understanding is required of how they are distributed on the landscape, what their form is, how their form influences their function, and how external factors influence these

1.1. Research goal and objectives

The goal of this research is to improve the understanding of Canadian mountain peatland abundance and subsurface form and how beaver affect both of these. Specific objectives are to:

1. determine the distribution of beaver impacted wetlands in a defined area of the front ranges of the Canadian Rocky Mountains;
2. quantify the proportion of these which are peatlands;
3. determine the impact beaver activity has on one hydrological variable: the area of open surface water; and
4. describe the stratigraphy of peatlands that have beaver activity at the surface.

1.2. Literature review

This section reviews literature with respect to the research goal and study objectives. The current knowledge of peatland distribution in Canada and its importance as a national resource is described. This is followed by a summary of what is understood about the form of peatlands, both at the surface and subsurface. The present understanding of peatland function, in terms of generalised hydrology and biogeochemistry is then related to peatland form. Through this process, gaps in knowledge that will be addressed by this thesis are identified.

1.2.1. Peatland distribution

Canadian peatlands are found in several ecoclimatic provinces, namely the Boreal, Subarctic, Cordilleran, Cool temperate, Arctic, and Interior Cordilleran. Over 92% of these are found in the Boreal and Subarctic ecoclimatic provinces (Warner, 2005). In comparison, peatlands in the mountain region, considered to be approximately the same geographical area as the Interior Cordilleran province, make up only 0.6% (Warner, 2005). If considered purely by area, these peatlands may appear to be less important compared to other ecoclimatic provinces. However, ecosystem services provided by wetlands that are located near the headwaters of major rivers, such as those in the front ranges of the Canadian Rocky Mountains, have a disproportionate importance on watersheds (Stein et al. 2004). The hydrogeomorphic position of mountain peatlands means that they are influenced by both surface and groundwater (Stein et al., 2004). The interaction of surface and ground water, in conjunction with other environmental factors in turn influences the biogeochemical properties of these wetlands, influencing ecosystem services such as carbon accumulation and export, retention and release of nutrients and contaminants, nutrient cycling, maintenance of characteristic plant communities, maintenance of faunal communities and maintenance of landscape biodiversity (Stein et al., 2004).

1.2.2. Peatland Inventories

Inventories provide a baseline from which to develop appropriate research avenues that will best advance knowledge about the value and function of natural resources (Gustavson and Kennedy, 2009). As well, inventories are necessary for land management planning as they provide a basis to assess the impact of both natural and human influences. Finlayson et al. (1999) reviewed the state of wetland inventories globally, finding that they were not sufficient to help understand either their extent or condition. In Canada, current inventory work is being done by Ducks Unlimited (Fournier et al. 2007). They are building a wetland inventory which, so far, covers large parts of Canada (http://maps.ducks.ca/cwi/). This inventory is extremely useful in understanding the general distribution of wetland and wetland type throughout the country, and forms an excellent platform for further research into wetlands and their management.

Although an important step in understanding the importance of peatlands is determining their distribution, inventories of peatlands in Canada and North America are incomplete. Inventories of peatlands in western Canada have been done at a broad spatial scale. Vitt et al. (1996) and Halsey et al. (1997) produced inventories of peatlands for Manitoba and Alberta, respectively. These inventories successfully identified tracts of peatlands, and provided estimates for land area percentage which is peatland. Although this provides a measure of peatland density, it does not provide a great deal of information on their specific location on the landscape, which is needed to direct land-use planning, assessment and management of cumulative effects to wetlands, and natural resource management and restoration strategies (Westbrook and Noble, 2013). At a more site-specific scale, Zoltai et al. (2000) produced a wetland database which includes physical measurements and chemical analyses of peat from 425 wetlands in Canada. This inventory only included three wetlands within the Canadian Rocky Mountains, all located in the High Arctic ecoclimatic region of the Northwest Territories. These three peatlands (organic soils were 74-236 cm deep) were described as being polygonal peat plateaus, treeless, and very poor in nutrients. There has been interest in inventorying wetlands in the mountain regions of the western United States. For example, Chadde et al. (1998) compiled 61 studies of peatlands in the northern Rockies of Idaho, Washington, Montana and Wyoming. As this is a compilation of studies, it is does not form an inventory as there is no indication of general distribution of peatlands in the region. However it does give an indication of the ecological value and diversity of mountain peatlands to determine priorities for fen restoration. In Colorado, Chimner et al. (2010) inventoried peatlands in the San Juan Range. They used a combination of field visits and GIS analysis in this inventory and documented approximately 2000 peat-forming fens.

Wetland inventories are generally carried out using remote sensing, either from aerial images or satellite images, and validated by ground truthing. Manual analysis of aerial imagery can be carried out to determine surface features that are representative of wetlands, such as vegetation type (Fournier et al., 2007) and basic hydrology (Halsey and Vitt, 1997). Satellite imagery is also used, with spectral analysis a popular way of identifying different vegetation type associated with wetlands (Fournier et al., 2007). In general, aerial images are used for inventories over a smaller area, as collection of these images is expensive, and their analysis time consuming (Fournier, 2007). Satellite images are generally used for larger areas, such as national inventories, as they have a much wider coverage. However, this also results in lower resolution making wetland identification more difficult (Fournier et al., 2007). Ground truthing allows site specific data to be gathered, such as wetland type and depth of soil (Zoltai et al., 2000), but this is a labour intense process which results in limitations to the number of wetlands that can be identified. Wetland inventorying methods are still advancing; for example, Brooks et al. (2013) discuss the challenges and future direction of wetlands inventory in the Mid-Atlantic Region of the United States. They suggest that maintaining an accurate inventory is not sustainable, but that the quality of existing inventory can be enhanced through the use improved techniques such as LiDAR to help capture smaller wetlands or wetlands occluded by forest canopies (Lang and McCarty, 2009; Halibisky et al., 2013).

1.2.3. Factors influencing peatland form

Peatlands, in general, are very sensitive to subtle changes in hydrological and ecological factors, as well as climate (Bragg, 2001; Charman, 2002; Pyne-O'Donnell et al., 2012). As a result, environmental factors can influence the form and thus function of a peatland. Environmental factors like volcanic eruptions (Pyne-O'Donnell et al., 2012), natural climate variation like the mid-Holocene Hypsithermal interval (Davis, 1984; Kuhry and Turunen, 2006), wildfires (Kuhry, 1994; Kuhry and Turunen, 2006) and floods (Bhiry et al., 2007) all of which can influence the soil-forming processes and thus regulate the stratigraphy of a peatland. The sub-surface structure can thus change as the peatland develops (Charman 1995; Loisel, 2013). The relationship between surface and sub-surface structure is reciprocal. Subsurface structure influences the storage capacity and permeability of the soils, which in turn influences the way that water flows through the peatland (Holden, 2008). This can affect water table dynamics (Whittington and Price, 2006), which is a major factor controlling the composition of surface vegetation (Strack et al., 2006). Since peatlands are living entities, vegetation at the surface determines the type of peat that the peatland develops through time, influencing the future sub-surface structure. Peatlands, given their anoxic nature, thus provide a long term record of the signatures of these complex and interactive hydrological, physical and biological processes (Vitt et al., 2000; Pyne-O'Donnell et al., 2012; Chiverrell and Jakob, 2013). In a mountain environment, climate has an exaggerated effect on mountain ecology, geomorphology, and hydrology (Theurillat and Guisan, 2001; Pomeroy, 2004). Since temperature lowers as altitude increases, temperature can change rapidly over small areas. In mountainous regions, the boundary zone for where certain vegetation can exist is much more narrowly defined than in areas of lower topographic gradient. As a result, the shifting of these boundaries becomes more exaggerated and reactive to small changes in temperature. Mountains also represent a significant interruption to air-flow, which makes weather patterns less predictable. These factors mean that mountain peatlands are likely to have a more complex environmental record than those in less dynamic locations.

External biological factors, for example, beaver, can also influence peatland structure. There are two species of beaver. The North American beaver (*Castor canadensis*) is mainly found in the USA and Canada, and northern parts of Mexico. There are also introduced populations in northern Europe, Chile and Argentina. The Eurasian beaver (*Castor fiber*) is found across northern Eurasia. Both species of beaver are well known ecosystem engineers impacting the hydrology, geomorphology and ecology of areas they inhabit (Gurnell, 1998). The population of *C. canadensis* is estimated to be >9.7 million (Whitfield et al., submitted) and of *C. fiber* is ~1.04 million (Halley et al., 2012). Beavers were trapped to the brink of extinction prior to protective measures being introduced in the early 20th century. Since then the population in North America has recovered to approximately 10% of its pre-European level (Naiman et al., 1988).

The hydrological, geomorphic and ecological impacts of beaver dams in alluvial river systems are well described in the literature (Naiman et al., 1988; Gurnell, 1998, Westbrook et al., 2006). The current conceptual model of beaver impacts on river systems is the beaver meadow formation (BMF) theory. In it, sedimentation in beaver ponds eventually leads to the formation of beaver meadows (Ives, 1942; Terwilliger and Pastor, 1999). This landform is the result of damming and ponding, which inundates riparian areas and kills the majority of the existing vegetation. The ponds gradually fill up with sediment, and can be completely filled if the dam is continually maintained by beaver. Or alternatively, an unmaintained dam may breach, draining the pond and exposing the deposited sediment. Both outcomes produce a fertile sediment deposit which is quickly colonised by a variety of plants and shrubs different to the surrounding vegetation (Fig. 1).

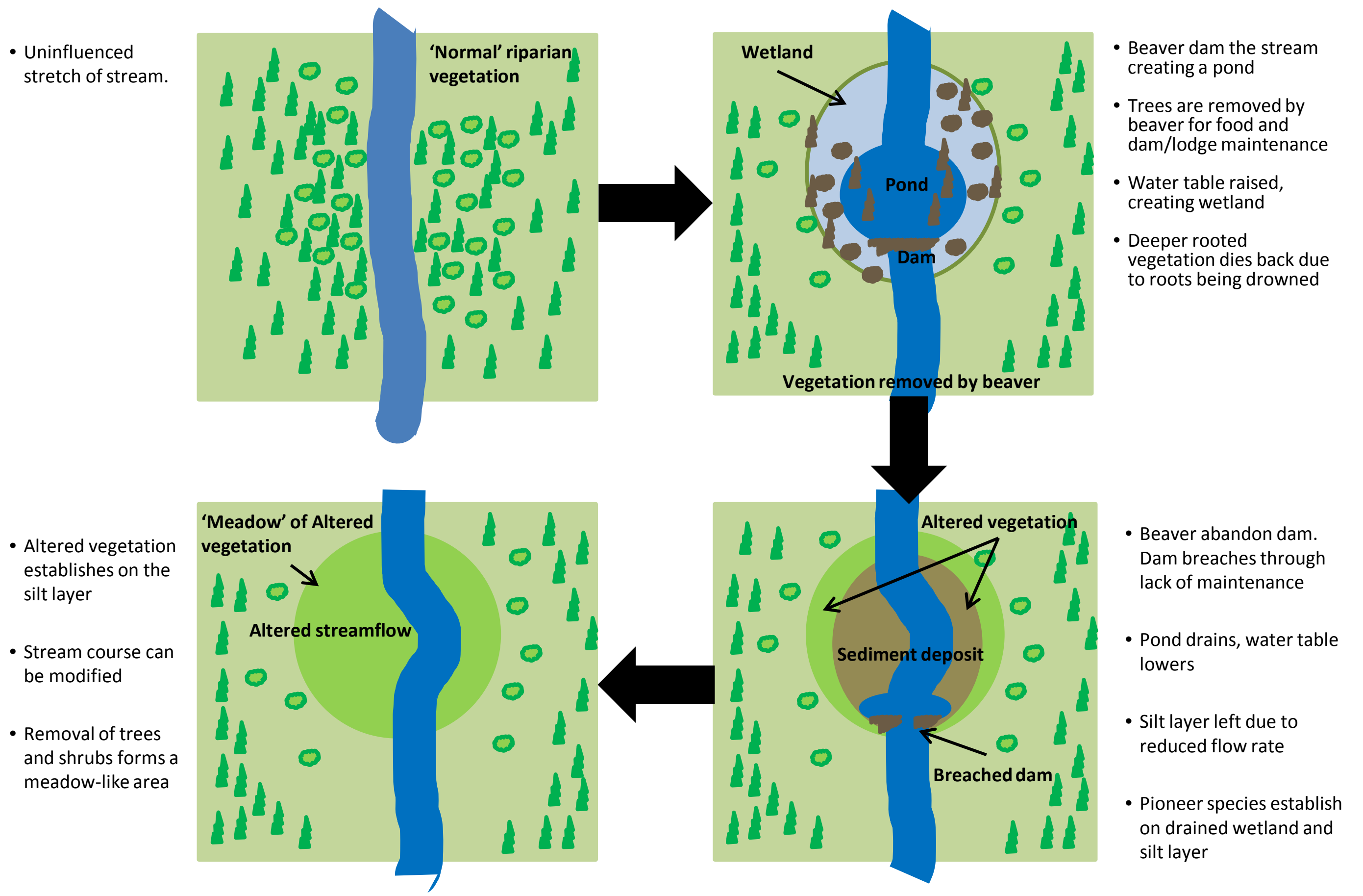


Fig. 1 - Beaver meadow formation process for riverine systems

It is generally agreed that beaver ponds store sediment by reducing water flow speeds and allowing settlement of sediment (Ruedemann & Schoonmaker, 1928; Butler & Malanson, 1995). Newer research has shown that beaver dams influence sediment deposition beyond just the pond. John and Klein (2004) showed that dam building by the Eurasian beaver caused significant deposition on the flood plain, eventually leading to channel modification. They found sediment deposition reaching beyond the pond, onto the flood plain and onto terraces. Westbrook et al. (2011) showed a similar effect of *C. canadensis* with terraces forming 0.7 m – 1.2 m above the floodplain affected. Butler and Malanson (1995) describe beaver related sedimentation through excavation activities, such as canal digging. Polvi and Wohl (2012) investigated the importance of beaver related aggradation within Rocky Mountains National Park. They state that where the alluvial deposits covering glacial sediments are relatively thin, small magnitude beaver-induced sediment deposits represent significant aggradation. What is clear from the literature is that beaver have a major influence on hydrology and geomorphology of riverine systems. However, beaver have also been observed to inhabit pre-existing wetlands, including peatlands (Reddoch and Reddoch, 2005; Westbrook et al., 2013; Milbrath, 2013). Persico and Meyer (2009) gave several examples in an alluvial system where beaver-created sediment deposits left a stratigraphic record. If alluvial systems contain such paleological evidence of beaver influence on hydrology then it is likely that there will be an analogous stratigraphic record in peatlands, especially considering their proven ability to record environmental change (Pyne O'donnell, 2012).

People have had a significant influence on the beaver population over time. Trapping by European settlers led to the near extinction of beaver in North America. Although the population has recovered to an approximate 10% of peak numbers (Naiman, 1988), thanks to conservation efforts, human activity continues to influence beaver populations. For example, the annual beaver pelt harvest in the Province of Alberta has averaged 12,075 over the past 5 years (Government of Alberta, 2012). The distribution of beaver in the Rocky Mountains has not been documented, therefore it is difficult to assess the human influence on the population, and how this subsequently influences peatland function. As a result of climate change, the geographical range of beaver is predicted to expand and their population density increase in the interior of their range (Jarema et al., 2009). This could mean more areas of peatland being impacted by and being impacted by greater numbers of beaver. This would likely mean that the hydrogeomorphic influence of beaver in peatlands would become more pronounced.

The majority of research carried out on the sub-surface structural influence on peatland hydrology and biogeochemistry has been restricted to peatlands that have a continuous column of peat (Clymo, 1984; Vitt et al, 2000; Bragg, 2001; Charman, 2002). Even so, these studies have shown that peat composition changes throughout the column, from a relatively permeable upper layer (acrotelm), to a relatively impermeable lower layer (catotelm) (Vitt, 2000; Holden, 2008). This heterogeneity in the peat matrix influences the hydrology of the peatland and therefore the biogeochemistry (Holden, 2008). But, there are many documented cases of much more complex stratigraphy in peatlands that extend beyond heterogeneities in the peat type. Many of these studies, which are focused on describing long term environmental change, document the intrusion of mineral material in an organic matrix (Table 1).

Table 1 - Stratified peatland studies

Paper	Study description	Description of stratification	Methods used
Pyne-O'Donnell et al., 2012	Investigation of buried volcanic ashes in Nordan's Pond Bog, Newfoundland.	12 discrete ash layers found within core sample, taken to a depth of 7.2 m. Eight attributed to known volcanic events (Mt. St Helens - c1000y BP, White River Ash - c1500 y BP, Newberry Pumice - c2000 y BP, Mt. Augustine - c2500 y BP, Aniakchak Tephra - c3500 y BP, East Lake Tephrac - 7000 y BP, Mazama ash - c9000 y BP).	Core.
Loisel et al., 2013	Investigation of peatland lateral expansion rate. Petersville peatland, Alaska.	Peat interbedded with one volcanic ash layer approximately 1.2 m deep, extending to at least 500 m. Thickness ranging from 15 - 25 cm. (Mt. Hayes eruption - c4000 y BP)	Cores and GPR.
Broder et al., 2012	Peat decomposition in 3 ombrotrophic bogs in southern Patagonia, Chile.	One bog had a clear volcanic ash layer between 150 and 200 cm depth (Mt. Burney eruption - c4250 y BP).	Cores.
Charman et al., 1995	Using volcanic ash in peatlands to investigate the variability of environmental change as a result of volcanic activiy through the Holocene. Strath of Kildonan, Scotland.	Three ash layers identified; 180-190 cm, 50-60 cm, 10-20 cm (unattributed, but one layer likely to be from Hekla 4 eruption, Iceland - c4250 y BP).	Core.
Tiit Hang et al., 2006	Dating volcanic ash found in 2 Estonian peat bogs.	One bog recorded as having ash material from 266-270 cm and 312-316 cm. Second bog did not show any ash (Hekla 4 eruption, Iceland - c4250 y BP).	Core.

Table 1 provides examples, but not an exhaustive list, of studies describing mineral intrusion. The field of tephrochronology (using buried volcanic ash layers in sediments to date eruptions) regularly studies peat columns to identify volcanic ash layers interbedded with peat. These studies are not concerned with peatland function, rather the intent is to date volcanic events, and assess their impact on climate through prevailing vegetation pre- and post-ash deposition. The majority of research (e.g. Clymo, 1984; Waddington and Roulet, 2000; Bragg, 2002) describing peatland function has been restricted to 'pure' peatlands. Therefore, models of hydrological and biological processes in peatlands may need to be rethought, considering peat form varies more widely than is currently described.

1.2.4. Influences on peatland function

Peatland and function is influenced by both surface and subsurface structure. The subsurface structure of peatlands affects their hydrologic and biogeochemical function (Reeve et al., 2000; Holden, 2008). Internal peatland structure influences the rate at which water flows through a peatland (Holden, 2008) and the dynamics of water movement through a peatland in turn influences biogeochemical processes such as carbon sequestration (Roulet, 1990; Bragg, 2001).

Surface water cover, surface vegetation and climate can alter the amount of water a peatland stores. Water table dynamics control the nutrient exchange zone in the soil, influencing the rate at which nutrients are cycled and the rate of carbon sequestration (Vitt et al., 2000; Bragg, 2001). Beaver are currently affecting the surface of Rocky Mountain peatlands (Janzen and Westbrook, 2011; Milbrath, 2013), creating dams, ponding water, and changing vegetation through inundation and browsing. Beaver have a clear impact on the surface of peatlands which in turn is likely to influence their function. However, there is little work describing such effects. What is known is that beaver create ponds in peatland by damming seepage and digging canals to divert water (Westbrook et al., 2013). It is also known that beaver population has increased in step with peatland area throughout the Holocene (Gorham et al., 2007) and is predicted to increase in density and range as a result of climate change (Jarema et al., 2009). If beaver have inhabited peatlands throughout the Holocene, then it is likely that they have had a continuous influence on their surface and sub-surface form, function and development. It is, then, also likely that human influence through near eradication, protection and current management activities likely contribute to the level of beaver influence on peatlands.

1.2.5. Current research gap

Peatlands occur in many areas of the northern Rocky Mountains, but there is no current inventory describing their distribution. Without this inventory, it is difficult to assess the external influences, both natural and human, on the function of these peatlands, and therefore develop appropriate land management strategies. The literature shows that the surface and sub-surface form of peatlands affects the ecological services they provide. Therefore, there is a need to understand factors that influence these forms, as any change will likely result in a change in the ecological services provided. Although beaver inhabit mountain peatlands (Westbrook et al., 2006; Janzen and Westbrook, 2011) and other ecoregions (Racine and Walters, 1994; Walbridge, 1994) throughout the Holocene (Gorham et al., 2007), little is known about how beaver impact peatland form and function. Questions that arise are: How many wetlands in mountain environments are affected by beaver? How many of these are peatlands? How do beaver impact the subsurface form function of peatlands? Questions like these need to be answered to begin to understand the various influences on peatland development. Understanding the services peatland ecosystems provide, how they have developed, factors controlling their development, and how future scenarios may alter these systems, is essential in developing appropriate management strategies that will provide the best benefit for both society and the environment.

2. METHODS

2.1. Study Site Description

The study was conducted in the Canadian Rocky Mountains west of Calgary, Alberta, in a 7912 km^2 area consisting of mountains and foothills (Fig. 2). Water originating from the Rockies represents the main water supply system for much of the three prairie provinces. Water passes through many of the wetland systems as it flows from the peaks to the lowlands. Understanding the numerous interactions of this system is essential for improved water management in Western Canada, as supplies experience more stress due to agricultural demands, urbanisation and climate change. Included in this study area is the entire Kananaskis Country parks region, part of the Stoney-Nakoda First Nations Reserve and three Municipal Districts (Fig 3.). This area is known to support a beaver population and an active research project on beaver in peatlands is ongoing near Sibbald Flats (C. Westbrook, pers. comm.), which known to have beaver and peat interspersed with mineral soil layers.

The boundary of the study area was largely influenced by the availability of recent (2007 and 2008) high resolution aerial images (Imagery metadata given in Appendix B), and the geographical limit of the foothills region (Fig. 3).

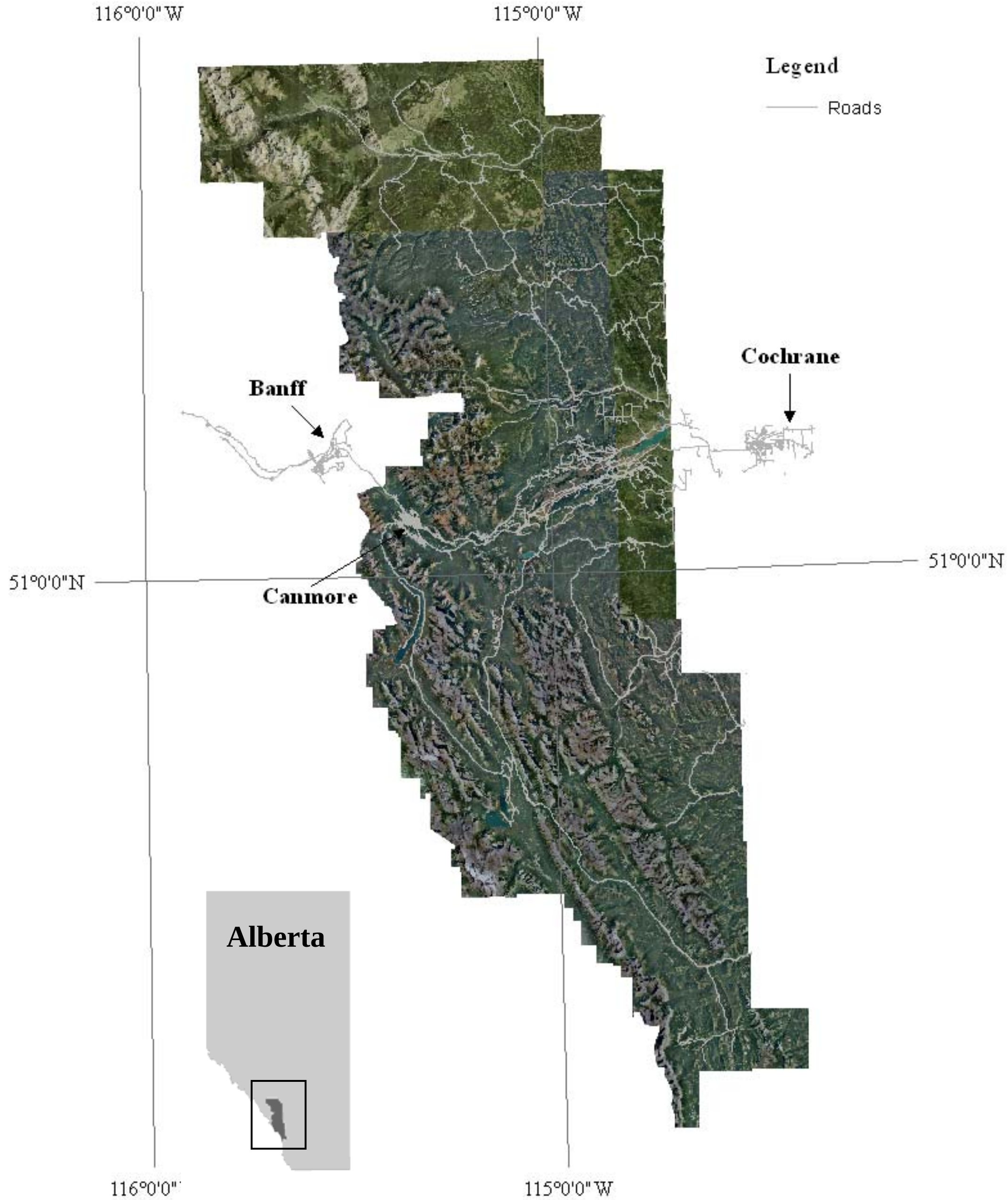


Fig. 2 – Study area, southern Alberta Rocky Mountains and Foothills

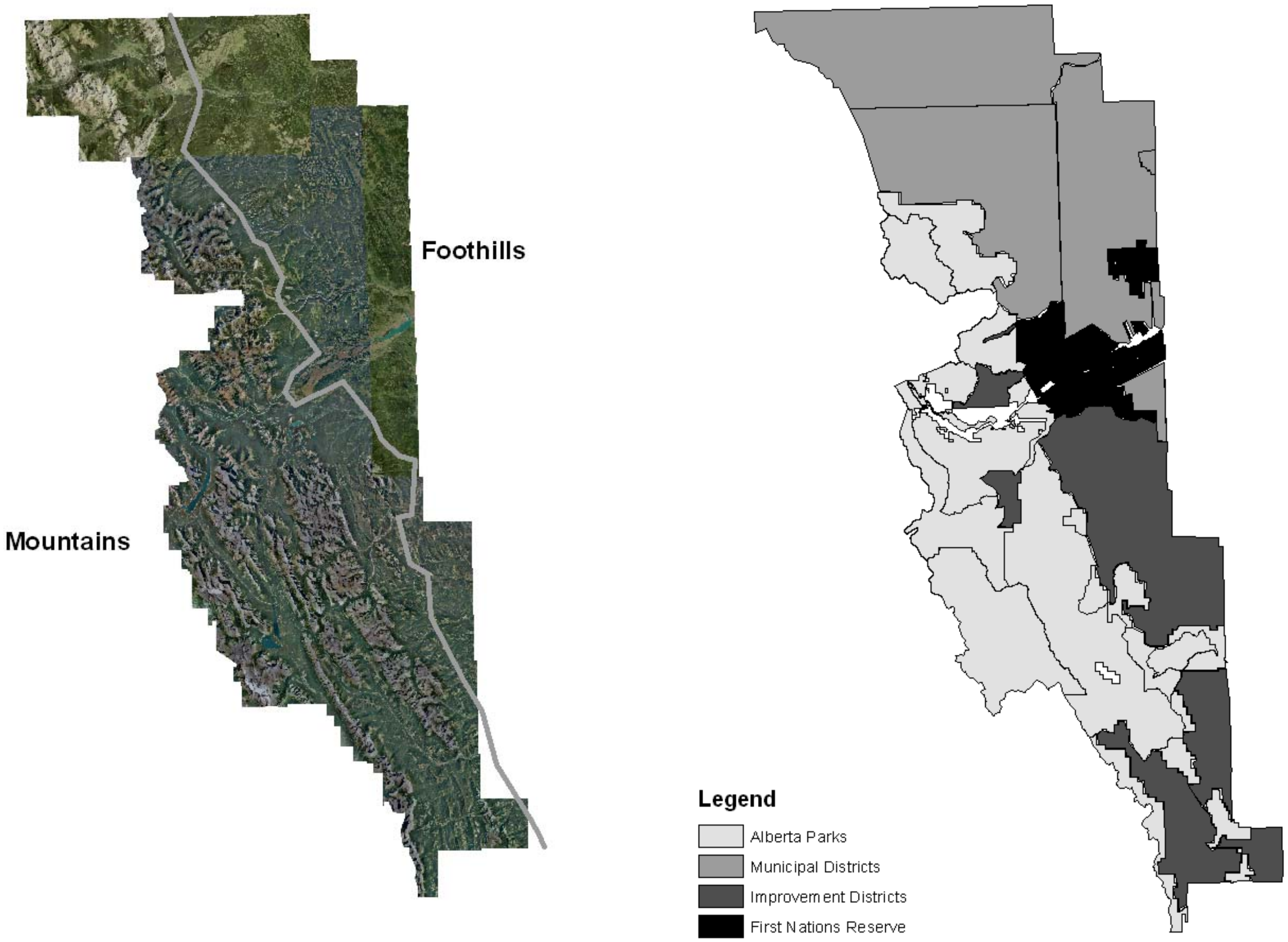


Fig. 3 – Physiographic (left) and Jurisdictional (right) divisions

Natural Resources Canada (http://atlas.nrcan.gc.ca/) classifies the wider region of the study area as having a land area that is wetlands percentage of between 1 and 8%. Wetlands are typically classified as, "…*land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment*" (Canadian Wetland Classification System, 1997). The elevation of the study area ranges from 1197 m to 3065 m above sea level. Higher elevation wetlands are located within steep-sided mountain valleys, usually surrounded by coniferous trees. Lower elevations wetlands are mainly located in the foothills, characterised by less steep slopes, unconstrained valleys and more varied land uses, such as ranching, recreational vehicle use, forestry and cattle grazing. Mountain and foothill regions were roughly delineated (Fig. 3) by the change in relief from steeper gradients to more shallow ones using 1:50,000 topographic maps and a 1 m digital elevation model (available from geobase.com).

Peatlands have been previously documented in the study region. The basal date of peat soils in the upper Elk Valley, a glacial valley connected to the south of the study area, yielded an age of 13,450 (± 450) years BP (Ferguson and Osborn, 1981). This suggests that the study area has been open to peatland initiation, and presumably beaver habitation, since that time. Gorham et al. (2007) found that peatland initiation lags behind deglaciation in North America by approximately 4000 years. This suggests that the location of Ferguson and Osborn's sampled peatland may have been free of ice for approximately 17,500 years.

The vegetation within the study area can be split into two separate zones, and is described by Hallworth and Chinnappa (1997). Briefly, the foothill zone is dominated by lodgepole pine, trembling aspen and white spruce. Shrubs found here include willow, juniper, bearberry, and bogbirch. The montane (roughly equivalent to the "mountain" region of the study area) zone consists of Douglas fir, white spruce, lodgepole pine and trembling aspen. Shrubbery includes juniper, bearberry, prickly rose and birch-leaved spirea. The montane zone can be subdivided into lower and upper sub-alpine. The lower sub-alpine zone (1200 m - 1800 m) has forested areas consisting of mainly lodgepole pine and Engelmann spruce, the latter of which dominates very wet areas. Aspen forests are also found in areas of fine silty soil. Shrubbery in this zone includes Labrador tea, bracted honeysuckle and Canada buffalo-berry. The upper sub-alpine zone (1800 m - 2300 m) consists mainly of Engelmann spruce and subalpine fir, with alpine larch extending several hundred metres below the treeline. Subalpine meadows are a feature of very wet areas.

Most wetlands are located on valley bottoms or plateaus on slopes. They are typically fed by small streams, diversion of water from larger streams, or groundwatersprings . Higher elevation wetlands tended to receive water from a small stream, or an adjacent larger stream that would flood into the wetland occasionally. The study area has a boreal climate. Fieldwork was carried out between 1 July 2012 and the 20 August 2012. Table 2 summarises the temperature and precipitation data recorded during the study period, as well as long term averages for the same months. The two weather stations used were Banff (WMO ID 71122, elevation 1397 m), which was outside of the study area but in a similar physical setting, and Kananaskis (3053600, elevation 1391 m), located within the study area approximately 20 km south of Highway 1 on Highway 40.

Table 2 - Study area climate data

	Mean daily temp (deg C)		**Total prec. (mm)(% snow)**	
	2012	**1977-2000**	**2012**	**1971-2000**
Banff (WMO ID 71122, 1397 m)				
June	10.4	12	163.4*	61.7 (3%)
July	15.5	14.6	35.8*	54.2 (0.2%)
August	14.8	14.1	16.4*	60.1 (0.2%)
January	-7.8	-9.3	14.8*	27.5 (89%)
Kananaskis (Climate ID 3053600, 1391 m)				
June	11.2	11.4	241 (0%)	89.7 (1%)
July	15.9	14.1	68.8 (0%)	68.9 (0%)
August	14.9	3.6	54.4 (0%)	72.7 (0.5%)
January	-5.1	-7.5	34.4 (89%)	29.9 (97%)

** Data missing*

(Source – Environment Canada National Climate Data Archive)

It is likely that historically, beaver were extensively trapped in the study area, similar to other parts of Canada. Several fur trading outposts were established nearby on the Bow River (Peigan Post), Kootenay River (Kootenae Post) and the North Saskatchewan River (Rocky Mountain

House) (Moore, 2012). The history of trading with the Ktuxana, Piikani, and Niitsitapi First Nations (Moore, 2012) suggest that there was an abundant beaver population in the early 1800's.

2.2. Inventorying of wetlands

Inventory of beaver-colonised wetlands in the study area involved both a general analysis of aerial photography imagery in a Geographic Information System (GIS) and visits to a subset of wetlands.

Physiographic and jurisdictional wetland distributions across the study area were determined by creating a wetland database, based on wetland GIS shapefiles available from the National Topographic Database (NTDB). The extent of the study area was determined using the most recently available aerial imagery (2007 and 2008). The wetland shapefiles were overlaid on the aerial imagery and manually inspected to assess accuracy. Confirmation of wetland status generally relied on observing the water table at the surface, patches of low lying homogenous vegetation and more intensely green coloured vegetation. This assessment found that the majority of the wetland polygons coincided with apparent wetlands on the aerial images. The accuracy of the shapefiles was also assessed during ground-truthing, where 100% of wetland sites identified from the shapefiles proved to be wetlands on the ground. The UTM coordinates of the centroid and area of each wetland within the study area were recorded as well as the physiographic and jurisdictional region it fell into. These data formed the basis of the wetlands database.

2.3. Identifying wetlands with beaver activity

Individual wetlands were assessed for beaver activity by visually inspecting the aerial images. Two basic identifiers were used. First, ponds that had clear indications of being created by beaver (Fig. 4 a&b); identifying features include ponds, dams (linear structures) and lodges (circular features within ponds. Second, relict structures were identified which clearly indicated past beaver activity, but were not accompanied by the presence of ponded water on the surface at the time that the image was taken (Fig. 4 c&d). These include relict dams (broken linear structures) and patches of relatively homogenous vegetation of sedges and grasses that were different than the surrounding area (see Wright et al. 2003).

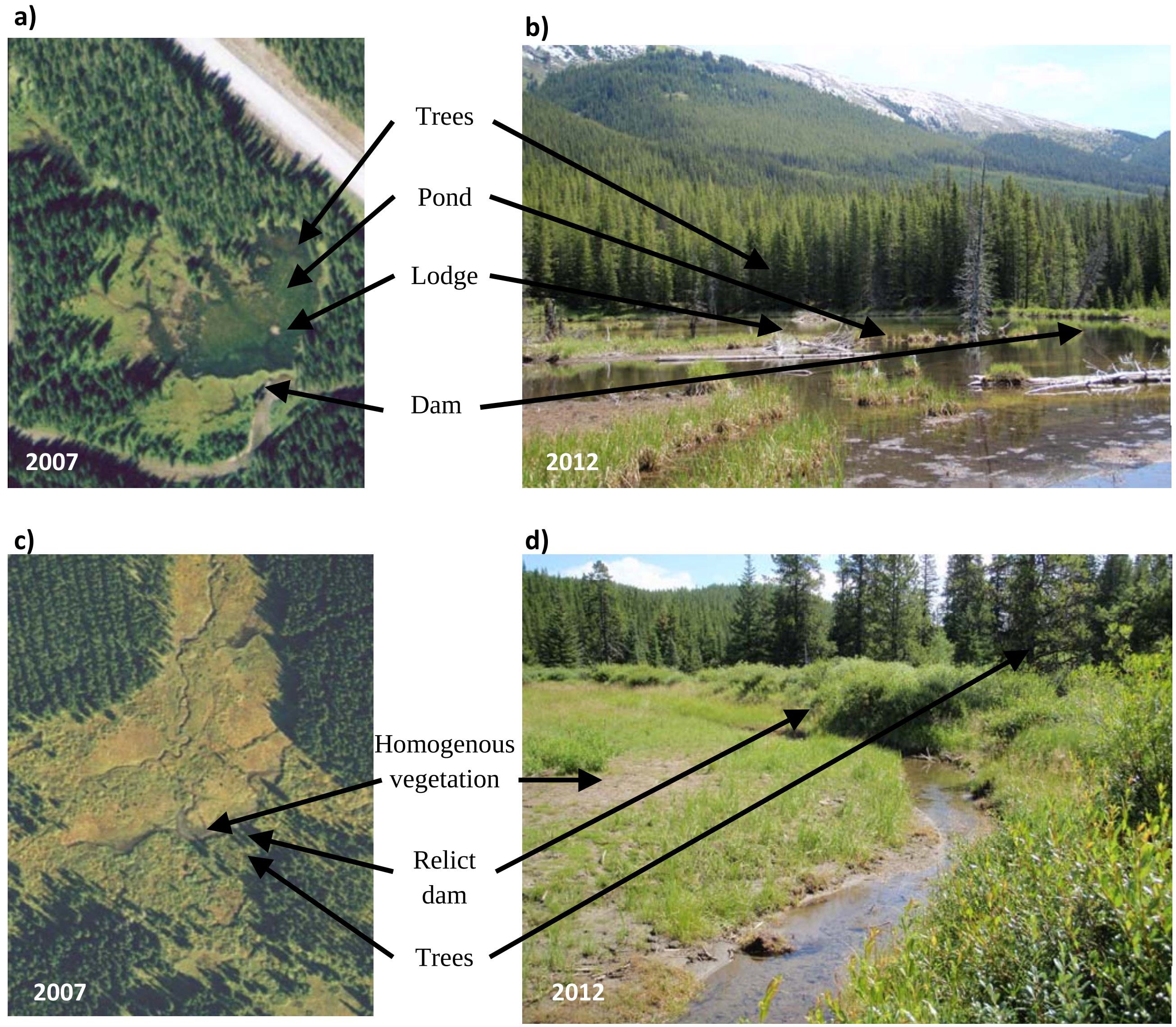


Fig. 4 - Identification process example for beaver impacted wetlands

Beaver-related features were assessed remotely, and subsequently ground–truthing was performed for 15% of the 529 inventoried wetlands. Ground Penetrating Radar (GPR) site surveys were to be carried out on beaver impacted wetlands therefore more of these sites were selected for field visits. However, it was also necessary to visit non-beaver impacted wetlands to avoid biasing the inventorying of beaver impacted peatlands. A 3:1 ratio of impacted sites to non-beaver impacted site was chosen to balance these priorities. A ranked list of the 161 beaver impacted wetlands identified on the aerial imagery was created in the database, as was a number of other metrics like accessibility by road and number of wetlands nearby. A large number of non-beaver impacted sites were accessible and there were no selection criteria, other than they not show any evidence of beaver impact. It was possible to identify non-impacted wetlands that could be planned around visits to impacted wetlands. It was not expected that all wetlands on the list would be visited, rather that the list would be large enough to account for anticipated access issues. For example, some wetlands were on private land where access permission could not be obtained, and others were inaccessible due to poor trail conditions. Of the 129 potential wetlands listed, 81 were visited.

All sites visited were confirmed as wetlands. The desktop analysis predicted that 59 of these wetlands would have recent evidence of beaver impact and 22 would not. Ground-truthing showed that of the 59 wetlands predicted to show beaver impact, 97% were correctly identified. The two wetlands misidentified as having evidence of beaver impact were an oversight during the site selection phase, as confirmed by repeating the desktop methods for those sites. Of the 22 wetlands predicted to show no clear evidence of beaver, 86% were correctly identified. The three wetlands misidentified as not having evidence of beaver impact were a result of features being small and overgrown, and the aerial imagery not having the necessary resolution for identification. Therefore the desktop analysis was proven accurate, with limitations in photograph quality more likely to lead to an underestimate of beaver impacted sites rather than an overestimate. The smallest size of wetland identified by the desktop analysis was approximately 0.2 ha. The smallest identifiable area of open water in any wetland was 5 m^2. During ground-truthing, it was observed that there were a number of wetlands that were not identified by the GIS dataset used, and therefore it is likely that the total number of wetlands reported here is an underestimate. Further, wetland areas could have changed since the data layer was created, as wetlands are known to be dynamic.

2.4. Inventorying open water area on wetlands

The aerial imagery was further analysed to determine the area of open water in the wetlands. Open water was considered to be water ponded behind a dam, water pooling behind relict dams (many relict dams have small pools immediately behind to either side of a breach) and water ponded without a clear surface source (groundwater springs, high water table, etc.). Open water polygons were manually created (Fig. 5) in ArcGIS. Both the total open water area and the number of ponds for each wetland, at the time the imagery was acquired, were computed and added to the wetland database. The difference in total water area between beaver impacted and non-impacted sites was assessed for significance using a Wilcoxon rank sum test, as the data could not be assumed to be normally distributed.

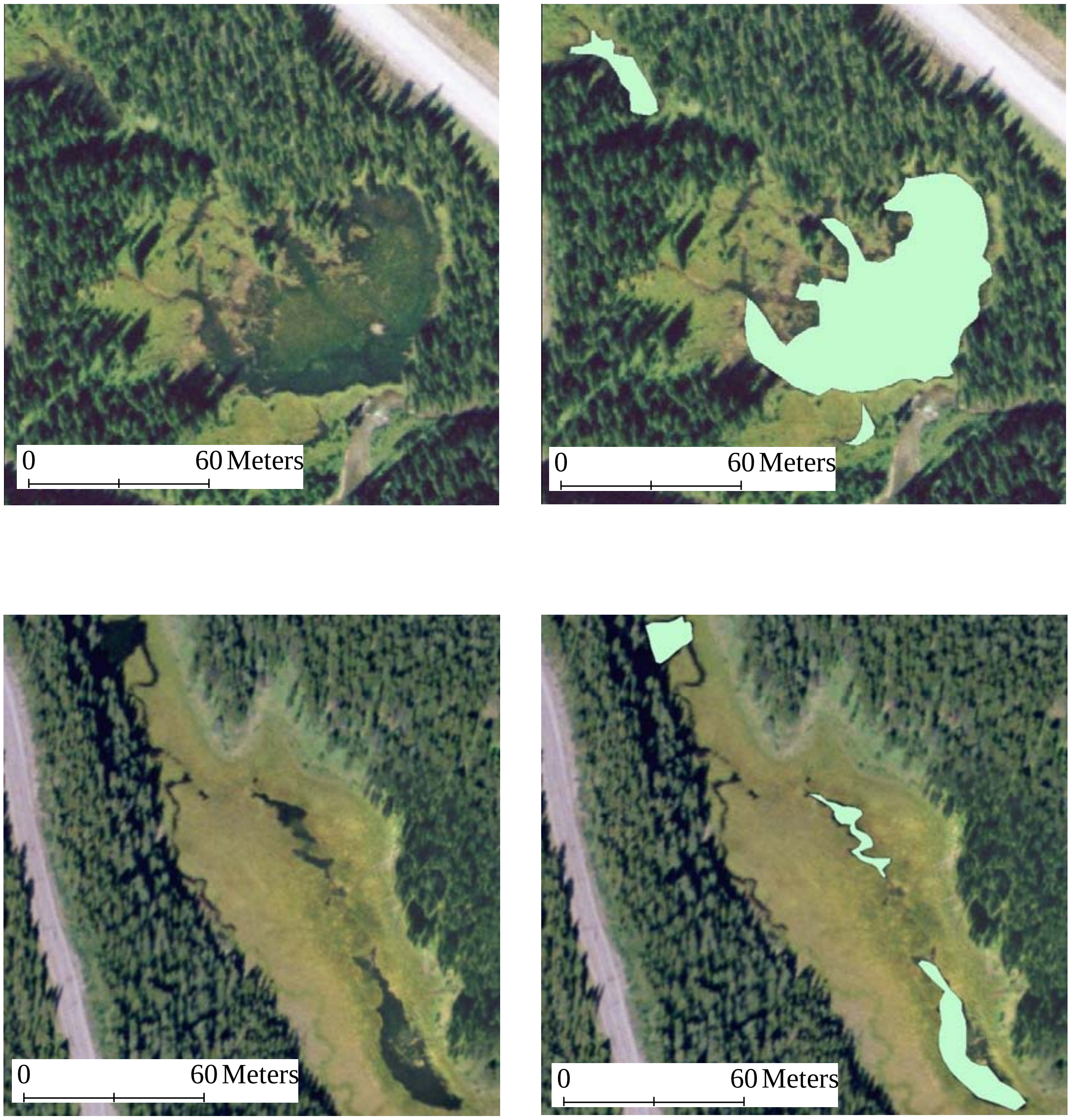


Fig. 5 - Delineation of open water features; beaver created (top), and non beaver created (bottom)

The aerial images were captured in 2007 and 2008. The 2007 images were taken in October, and contain 202 of the wetlands. The 2008 images were taken between August 15th and September 13th and contain 327 of the wetlands. The assessment of open water area is applicable only to the time that the aerial images were captured. Wetlands are dynamic systems and their extent and water content changes seasonally and annually, depending on climatic conditions. Therefore, due to aggregation of images from different years the assessment of open water area does not provide a snapshot of a single time period for the whole study area. However, these data are used to assess the impact of beaver on open water area, and although differences in extent of open water may exist year to year, the proportional impact is likely to stay the same. In terms of open water, the imagery from 2007 captures 194 out of 937 features (approximately 20%). It is not possible to quantify the difference in open water between years. However, climate data (Table 3) show 2008 to have been a slightly wetter year to the date of the photos than 2007. It also shows almost double the amount of precipitation by snow, and snow falling later in the year in 2008. This may have resulted in wetlands storing more water on average in 2008. Again, these data are used to compare number of open water features against beaver impacted and non-impacted wetlands, although total numbers may be affected, the proportionality is considered likely to be the same.

Table 3 - Climate data for the years of the aerial images (2007/2008)

	Mean daily temp (°C)		**Total prec. (mm)(snow)**	
	2007	**2008**	**2007**	**2008**
Kananaskis (Climate ID 3053600, 1391m)				
January	-4.7	-7.3	20.2 (19.0)	33.6 (33.6)
February	-6.4	-3.6	39.8	28.8 (28.8)
March	2.2	-1.1	47.8 (19.4)	25.8 (25.6)
April	2.3	0.6	62.6 (49.8)	45.8 (44.2)
May	8.4	7.6	102.8 (22.0)	291.2 (94.6)
June	12.2	10.9	175.8	151.4 (6.0)
July	18	13.9	13.2	73.6
August	12.6	14.2*	103.6	88*
September	8.5	9.5	104.8 (27.4)	90.2
October	5.5	n/a	32.4	n/a
			703 (137.6)	828.4 (232.6)

* Data missing

There is a small overlap of the image sets that give an indication of how open water area and number of pond features can vary annually as a result of beaver pond drainage (Fig. 6). Only one wetland with beaver impact coincided with this overlap, showing a large change in open water on that site between 2007 and 2008. This illustrates why the full data set should not be used to estimate open surface water area in the study area at any one time.

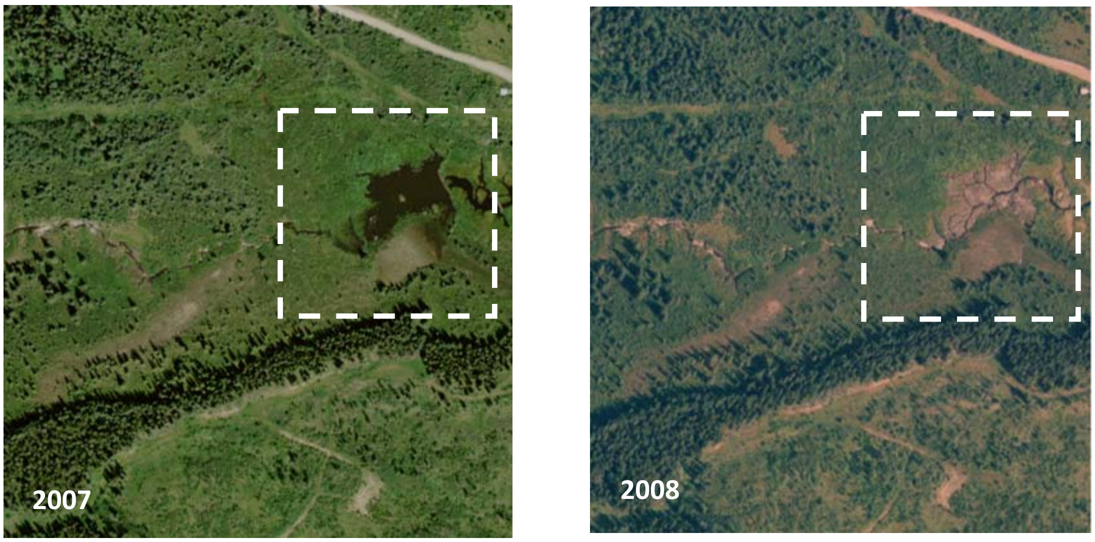


Fig. 6 - Annual variation in open water area

It is also recognised that there is subjectivity in this assessment of surface water area resulting from judgement of the water/vegetation boundary, as well as lack of clarity through pixel size of the photographs. This inaccuracy in relation to the results is addressed in the results section (Section 3.3).

2.5. Peat assessment

Soil sampling was carried out at each ground-truthed wetland (n=81) to determine if it could be classified as a peatland. There is no universal agreement on how a peatland is defined. Mitsch and Gosselink (1993) consider that a wetland must have at least 40 cm depth of peat (organic soil). Alternatively, Chadde et al (1998) (cited from Kivinen and Pakarinen, 1981) suggested that a peatland can be defined as a waterlogged wetland with approximately 30 cm or more of peat. Organic soil is defined in the Canadian System of Soil Classification (1998) as containing 17%

organic carbon, which is roughly equivalent to 30% organic matter by mass. So, soils with > 30% organic matter by mass were considered to be peat.

To assess peat content in each wetland, one soil sample was collected to a depth of 50 cm using a Russian peat corer. Samples were sealed on-site in polypropylene bags, refrigerated within 10 hours, and kept there until analysed in the lab. Samples were dried at 105^{o}C for 24 hours and then were burned in a muffle furnace at 500^{o}C for 5 hours. Samples were weighed before and after combustion to determine the percentage of organic matter. After ignition, samples were stored in a desiccant box until all were ashed in order to prevent absorption of water from the air before re-weighing. A G-test was used to determine the significance of peatland distribution with respect to jurisdiction and beaver presence. The G-test tests for independence between the variables ‘peatland’ and ‘jurisdiction’, and the variables, ‘peatland’ and ‘beaver impact’.

The published definitions of peatland were problematic for this study. Some wetland soils met the depth criteria in one or more core locations, but also failed to meet that criteria in one or more locations. For example, one core may have shown at least 50 cm depth of peat, but another core on the same wetland may have only shown 20 cm of peat. A further issue with using the described definitions of peatlands is that they are not clear if the peat depth should be a continous 30 cm or 40 cm. A number of wetlands showed over 30 cm of peat in the 50 cm core but this was not continuous, as peat soils were interbedded with mineral material (soil or sediment) (Fig. 7).

For these reasons, it was decided that a more general description of peatland would be suitable for this study. Therefore “peatlands” in this study include both wetlands that are true peatlands, i.e. consistent with the published definitions, and wetlands that are peat-forming. Peat-forming wetlands had at least 20 cm of peat or 20 cm of peat that contained minor lenses of mineral soil. For the analysis, peatlands and peat-forming wetlands were not separated. To avoid confusion, the term “peaty” is used hereafter to describe both. Peat type (sedge, moss, etc.) was not identified during this study.

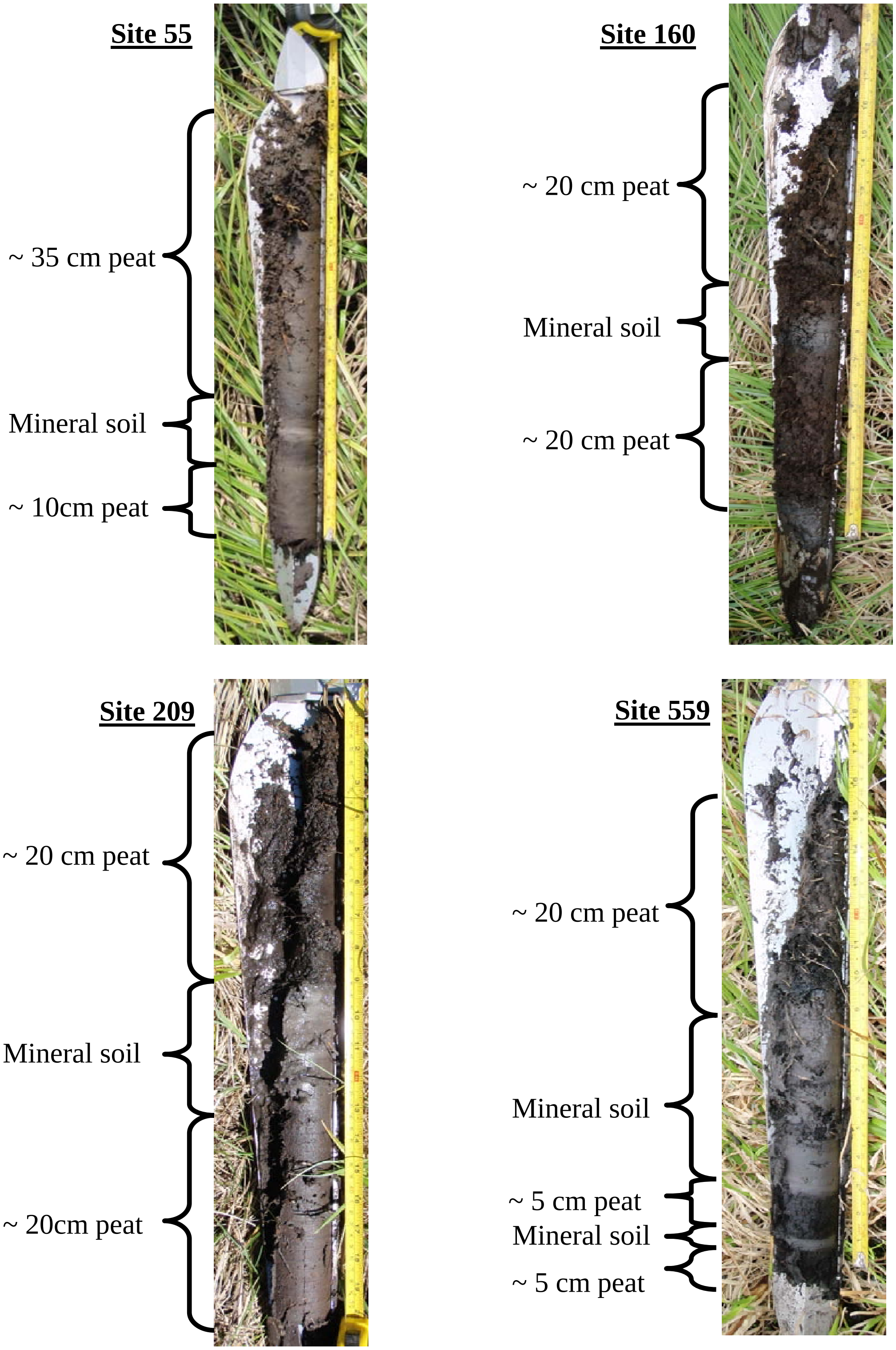


Fig. 7 - Core examples showing complex stratification of wetlands

2.6. Sub-surface investigation of beaver impacted peatlands

The way in which the GPR detects sub-surface objects and changes in soil structure is through sudden large changes in electrochemical properties. Therefore, each time the signal encounters a new material, the speed of the wave changes. The speed through each material is a function of the di-electric constant of that material and the speed of the wave. One effect of this is that the relative vertical magnitude shown on the GPR trace differs for different materials. For example, a 50 cm deep layer of peat will have a different vertical magnitude than a 50 cm deep layer of silt. Further complicating this is that two layers of peat interspersed by another material may have different electro-chemical properties to each other. Even further complicating this is that a thick layer of peat may have significantly different properties between the top and bottom of that layer, meaning that 5 cm at the top of the layer may have a different magnitude to 5 cm at the bottom of that layer. Without knowing the di-electric constant at every point, it is difficult to accurately measure the depth without the use of CMP or using a known target. For this reason vertical depth was measured as the time it takes for the signal to travel from the antenna and back to the receiver. This is known as the Two Way Travel time (TWT).

During ground-truthing, suitable wetlands for subsurface imaging with GPR were identified. The GPR consisted of a GSSI^{tm} 200 MHz antenna with survey wheel, and SIR 3000 control unit. Equipment set-up parameters such as, two way transit time, number of gain points, and gain levels, varied between wetlands and resulted in minor differences in survey strategy. GPR traces were analysed using RADAN 7 software provided by the manufacturer (GSSI^{tm}). The general procedure and individual site set-ups are given in Appendix C. Constraints were put on the selection of surveyed wetlands due to the method of operating the equipment and its size. Specifically, the GPR antenna requires a good continuous contact with the ground for optimal operation. Therefore sites with minimal hummocky topography were preferred. The equipment was also heavy and awkward to carry, restricting site selection to wetlands within 2 km of a road. Working within these constraints, 9 sites were chosen: 5 from the mountain area and 4 from the foothills area (Fig. 8). Five of these sites were confirmed as peatlands using the ignition testing of soil samples, as described in the methods section. The remaining four sites were shown to contain too little organic matter in their ignited samples to be considered peatlands. However, visual inspection of cores taken during the GPR surveys identified peat soil horizons. It should be noted that the identification of peat soil through ignition testing, and the identification of peat soil during GPR surveys are two different processes. Ignition testing was used as part of the determination of wetlands as ‘peatlands’, and core analysis on site during GPR surveys was used in conjunction with radar images to determine changes in the soil composition.

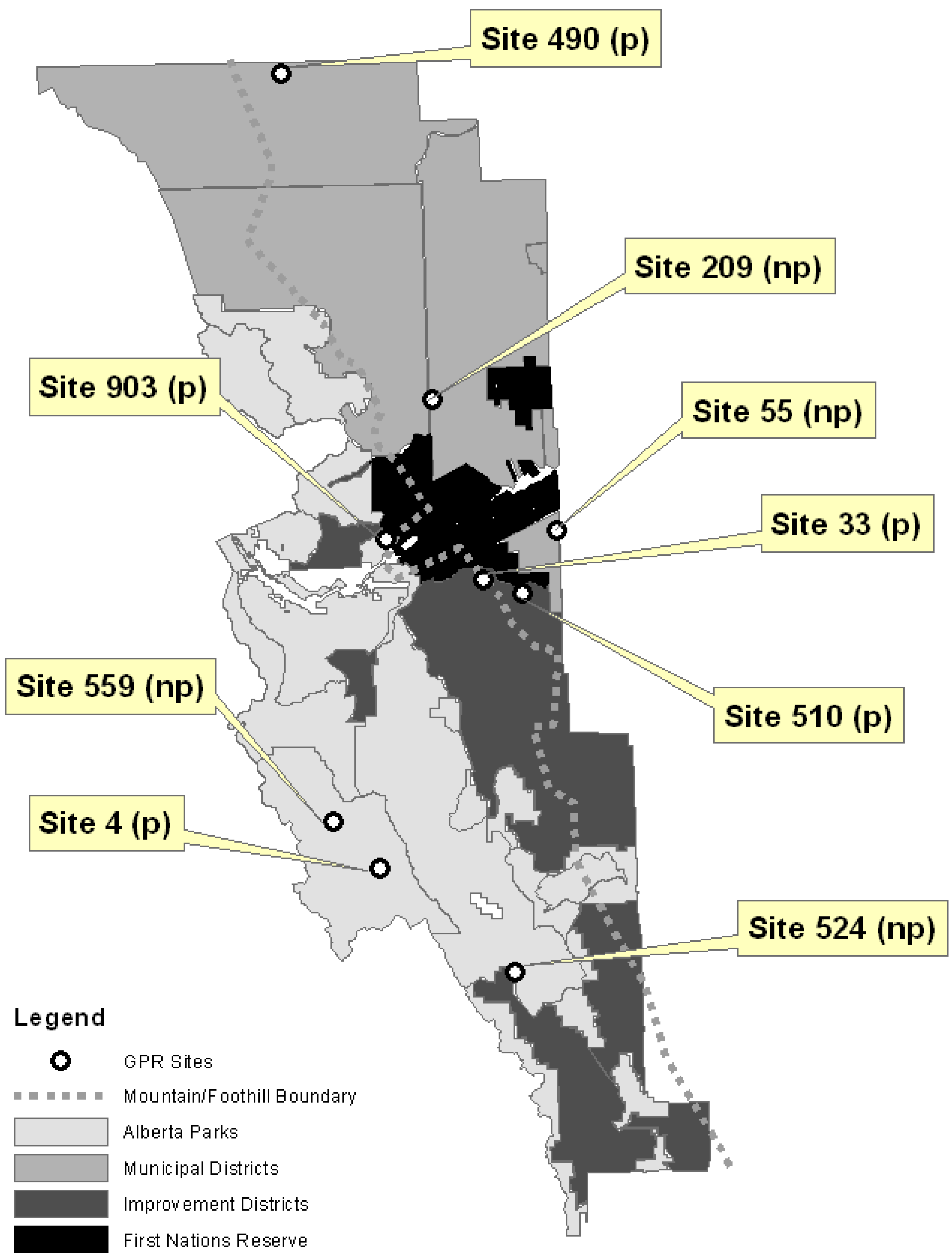


Fig. 8 - Location of GPR surveyed wetlands, (p) and (np) identify whether wetland is a peatland or not.

At each wetland, GPR surveys were carried out along transects. In general these transects were set perpendicular and intersecting each other to maximize wetland coverage. At least one of the transects was oriented parallel to the major water flow direction and as near as possible to the stream channel, where present. This was considered a sensible approach since beaver form dams and ponds by blocking the natural flow of water. By surveying parallel to the existing water channel, it was considered more likely to 'see' buried mineral lenses possibly originating from past ponding.

In practice though, it was not always possible to ensure transects were all parallel or perpendicular due to rough microscale topography. It was often not possible to follow an ideal transect due to sizeable hummocks or other obstacles (small shrubs or exposed root crowns from shrubs that had been previously killed by beaver) that made the GPR antenna lose contact with the ground surface. As a result, the surveyed transects were usually determined by the longest available stretches of ground without major obstacles. Still, some loss of contact with the ground surface occurred occasionally, resulting in signal distortion.

The method was first tested at site 33, Sibbald Research Wetland, where a known layer of mineral material occurs in the peat matrix (Janzen and Westbrook, 2011). This was also the most hummocky site, and lessons learned from the challenges encountered while imaging it were used to restrict selection of the other 8 sites.

Coordinates of the beginning and end of each transect and at regular intervals (ranging from 5 m to 20 m, depending on wetland size and transect length) were taken with a Trimble GeoXT, GeoExplorer 2008 series and a Trimble Tempest antenna, accurate to ±1 cm. These points were flagged. At each flag, a soil core was taken with an auger, and the stratigraphy was identified at 5 cm increments until the auger was fully extended (2 m to 2.5 m depending on the number of extensions available) or until it could no longer penetrate. The GPR antenna was then moved along each transect; core locations were marked on each trace to aid in data interpretation.

The variable measured by GPR is not depth but time as the depth depends on the speed of the radar signal through the soil, which varies with electrochemical properties. Conversion of time to depth is accomplished using the Common Mid Point (CMP) technique (Jol and Bristow, 2003). In this method the time to penetrate to a known target at a known depth is used. However, this requires a different GPR setup and antennae than was used in this study. To try to correlate time with depth, the soil core data were scaled to fit into the relevant layer shown on the trace. It is assumed that the core depth data are accurate. Cross-referencing radar traces with the core data aided in the analysis of the subsurface stratigraphy. Note that the thicknesses of the soil layers are likely to be reasonably accurate as they were assessed in 5 cm increments, but cores may be affected by compression, given that peat is highly compressible.

2.7. Ground Penetrating Radar interpretation

To allow for the interpretation of the radar traces, core data were matched to the corresponding points of the traces (Fig. 9 and 10). This comparison allowed different signatures in the traces to be matched to different materials extracted from the cores. Where signatures extended laterally from the core location on the trace, these were identified as continuations of the corresponding material from the core. For example, where mineral material was identified in a core and corresponded to a specific signature on the radar trace, which extended beyond the core location, the extent of that signature is considered to be mineral material.

In some cases, signatures were present that did not correspond to a core location, but resembled the signature of a known material at a cored location. For interpretation purposes, although the material cannot be confirmed, it has been considered to be an ‘assumed’ material (Fig. 10). For example, a signature that bears a strong resemblance to a silt signature, but begins and ends without coinciding with a core location has been considered to be “assumed mineral”. It is noted that the interpretation diagrams in the results section, and in Appendix C, ‘mineral’ and ‘clay’ material is identified. In this context, ‘mineral’ refers to soil which is non-organic in nature and usually grainy in texture, whereas ‘clay’ refers to what is assumed to be the clay base of the wetland beyond which the auger could not easily penetrate.

Using this process, simplified representations of the GPR traces were created to aid visualisation of the data (Fig. 10). It is recognised that this interpretation has some subjectivity in it, partly as a result of the complexity of the traces and their varying quality. The identification of ‘assumed’ materials is also necessarily subjective as it is based on the author’s interpretation of these complex traces.

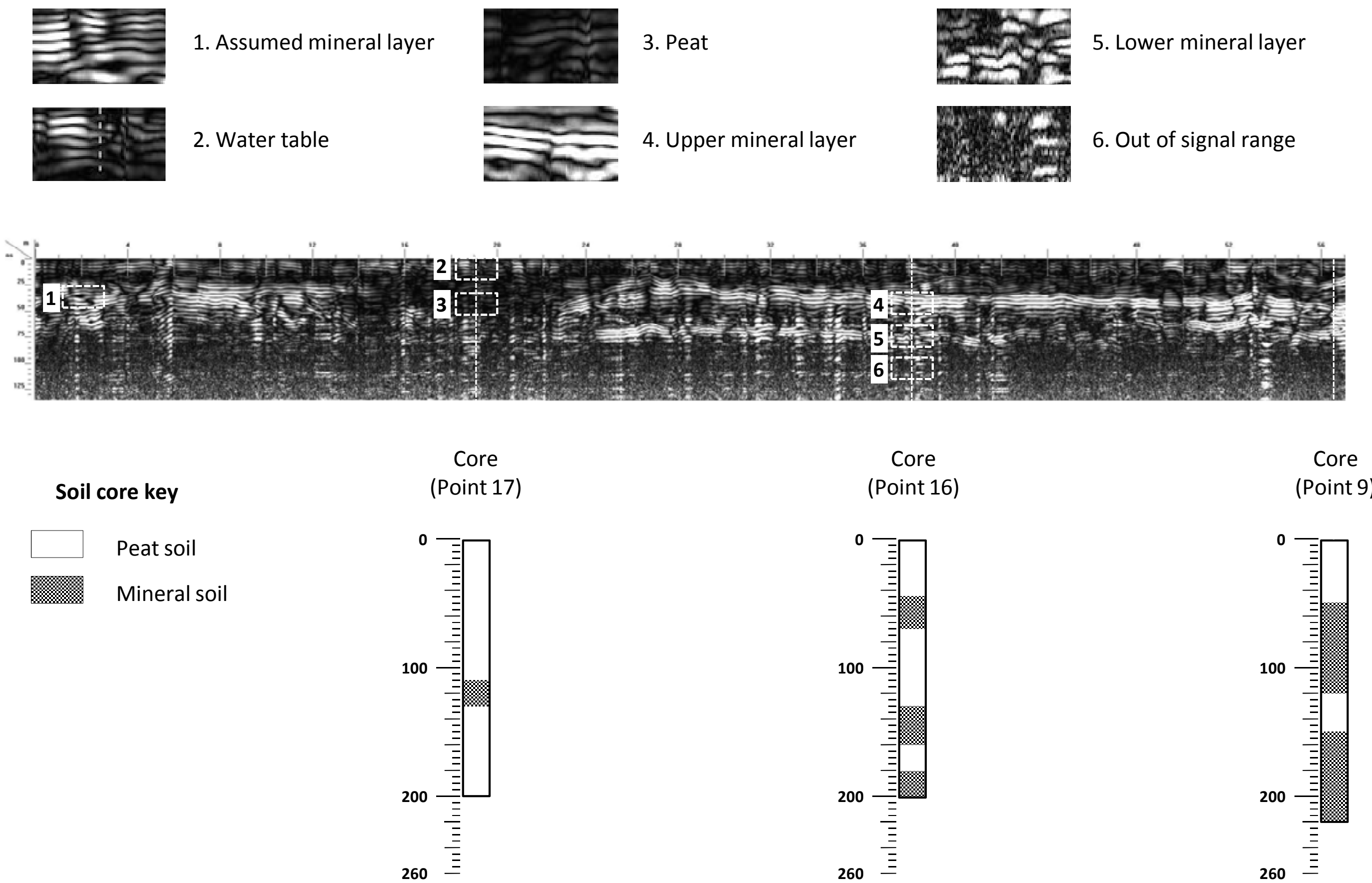


Fig. 9 - Interpretation of radar images and soil cores

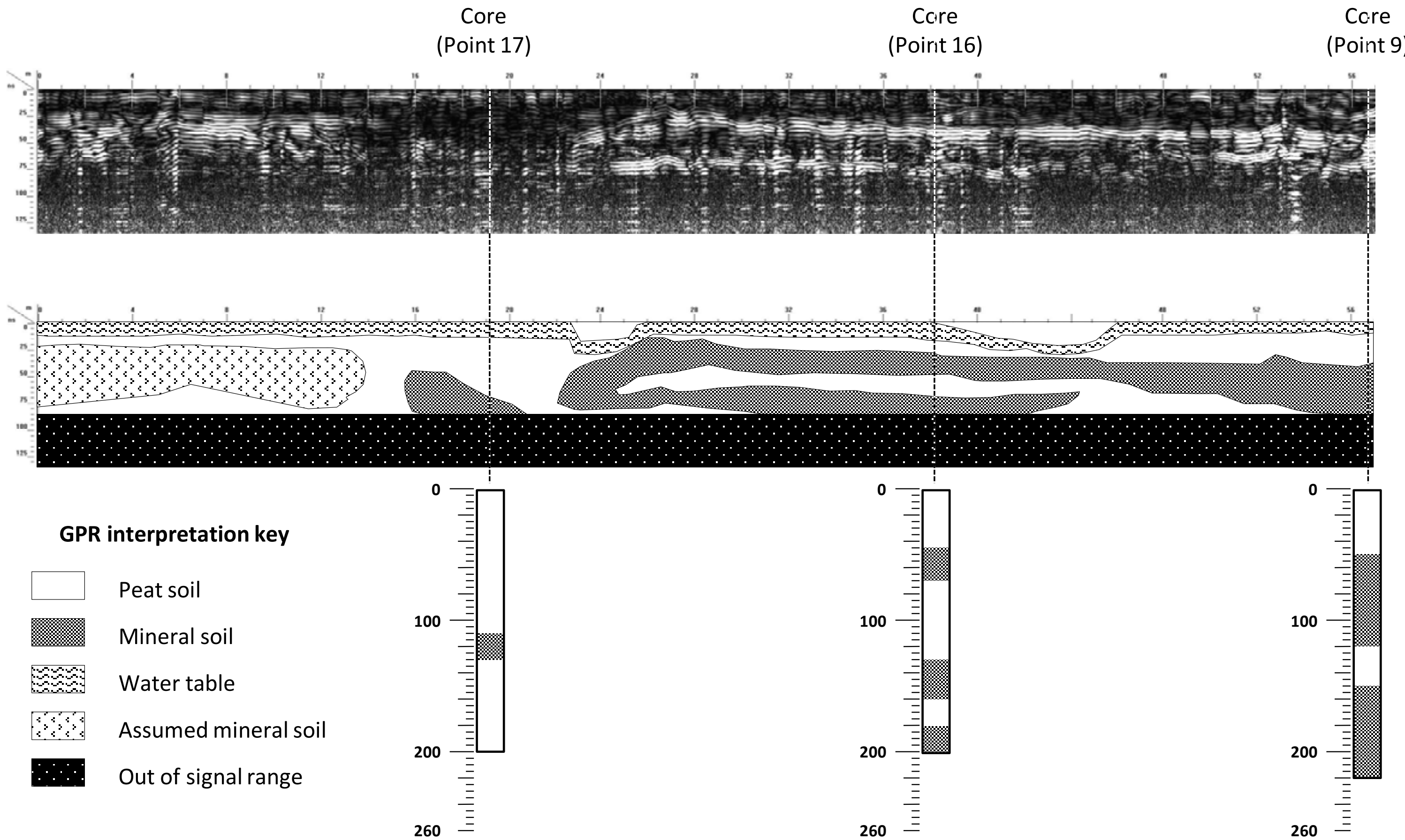


Fig. 10 - Interpretation of radar images and resulting diagrammatic representation

2.8. Assessment of mineral soil layering in wetlands

Strength of evidence of mineral soil layering in wetlands was assessed. This was done by counting the total number of cores taken and the total number of transects taken, and then comparing these to the total number of cores indicating peat lying above and below high mineral content soil, and the total number of radar transect images interpreted to show peat above and below soil with different electrochemical properties. Strong evidence was considered to be greater than 60% of cores and radar traces showing layering, moderate was considered to be between 30 and 60% and weak or no evidence considered to be <30%.

3. RESULTS

3.1. Distributions of wetlands and beaver impacted wetlands

Wetlands occur at elevations between 1215 m and 2194 m throughout the study area (Fig. 11). Beaver impacted sites are distributed across nearly the entire elevation range (1215 to 2152 m; (Fig. 11). Ground-truthed wetlands ranged from 1286 m to 1968 m (Fig. 11). Wetlands confirmed to have peat soils ranged from 1286 m to 1889 m (Fig. 11).

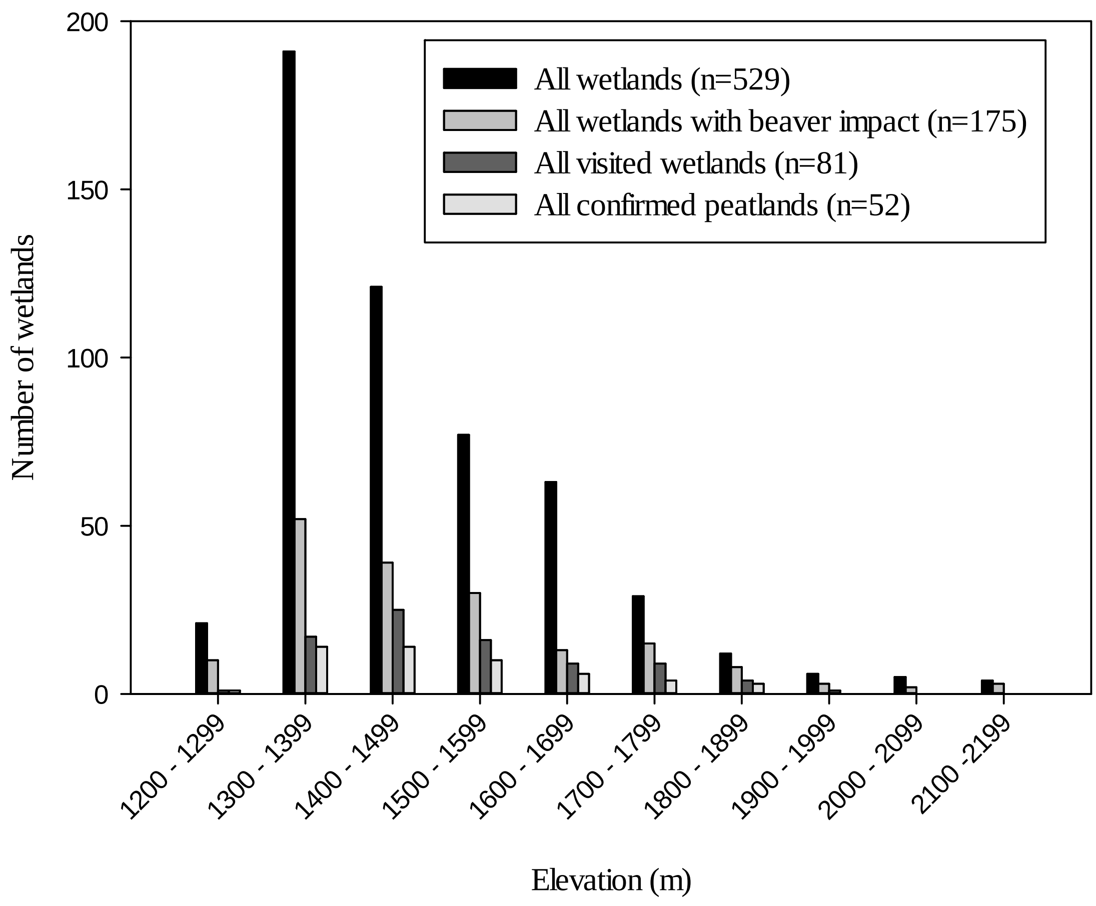


Fig 11 – Elevation frequency distribution of wetlands, beaver impacted wetlands, visited wetlands, and confirmed peatlands

Overlaying a 1m digital elevation model (DEM) of the region (Fig. 12) shows that wetlands are found mostly in valley bottom positions. This is very apparent in the mountain region where valley sides are steep, and valley floors are narrow, restricting wetlands to strings along the limited lower gradient areas. The DEM also shows this distribution is apparent in the foothills region, but that valley floors are wider and more undulating, and valley sides less steep. Although the wetlands in the foothills look more randomly distributed, the DEM shows that wetlands are still found mainly on valley bottoms.

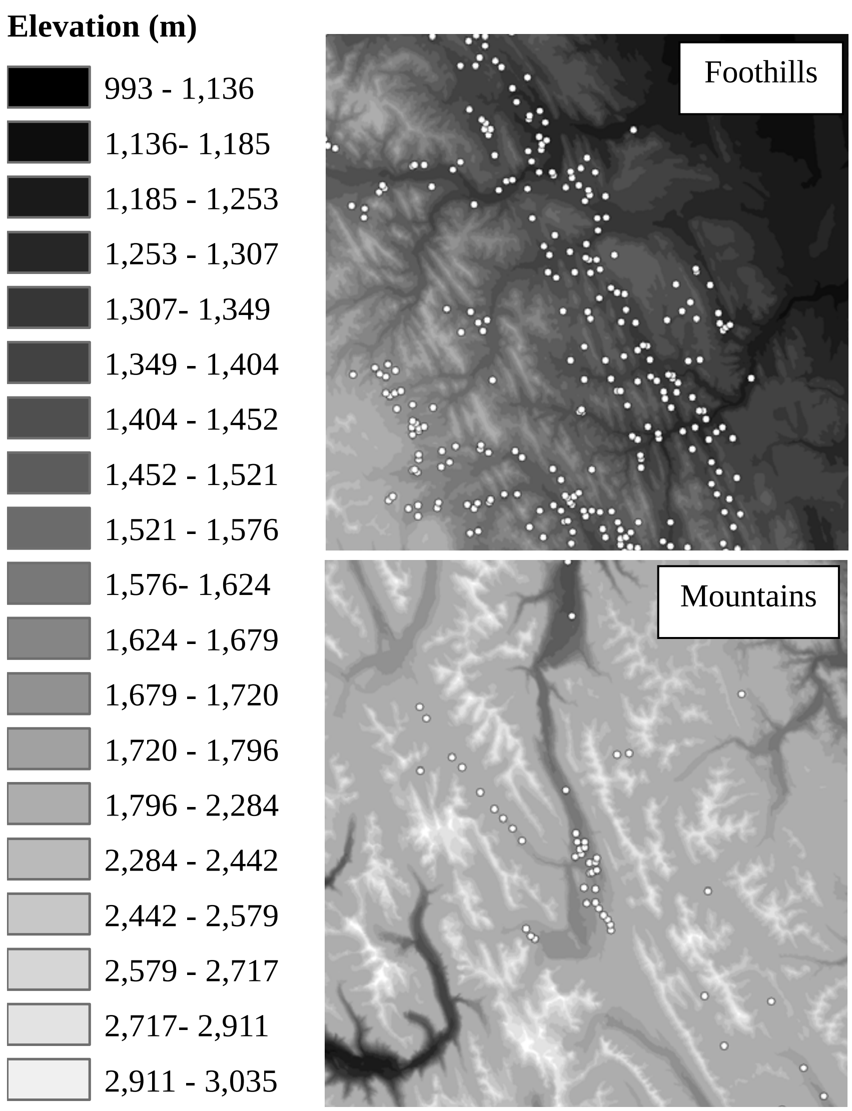


Fig. 12 – Distribution of wetlands (open circles) with respect to topography in Foothill and Mountain regions

Wetland distribution varied by both geographic location and jurisdiction. The GIS inventory of wetlands shows that of the 529 wetlands there are 133 (25%) in the mountain region, and 396 (75%) in the foothill region (Table 4). The number of wetlands per square kilometre across the whole study area is approximately 0.067. But, there is a clear difference between the geographical regions, with mountains having a wetlands density of 0.026/ km^2 and foothills of 0.137/km^2. Alberta Parks (0.020/ km^2) and Improvement Districts (0.026/ km^2) had considerably lower wetland density than Municipal Districts (0.121/ km^2) and First Nations Reserves (0.146/ km^2), reflecting the physiographic regions that these jurisdictions fall into. Table 4 shows how many wetlands were identified in each region.

Beaver have impacted 30% of all of the wetlands identified (Fig. 13). Distribution of beaver-created features differs by both physiographic region and jurisdictional region (Table 4). In the mountain region, 43% of wetlands have evidence of beaver impact (i.e., have existing dams and ponds, or relict features of breached dams and drained ponds), whereas only 26% of foothill wetlands do. Jurisdictionally, wetlands in protected areas (i.e., Alberta Parks 59% and Improvement Districts 60%) were most frequently impacted by beavers (Table 4). In contrast, the more densely populated Municipal Districts had few beaver impacted wetlands (20%). Roughly 40% of First Nations Reserve wetlands show evidence of beaver habitation. A clustering of beaver-impacted sites can be seen in the southeastern part of the Municipal Districts (Fig. 13).

Table 4- Distribution of beaver impacted and non-impacted wetlands

	Area km²	Beaver impacted		Non-beaver		Total
		No.	%	No.	%	
Physiographic location						
Mountains	5023	57	43	76	57	133
Foothills	2889	104	26	292	74	396
Jurisdiction						
Alberta Parks	2874	35	59	24	41	59
Municipal Districts	2975	74	20	287	80	361
Improvement Districts	1603	25	60	17	40	42
First Nations Reserve	460	27	40	40	60	67
Total	7912	161		368		529

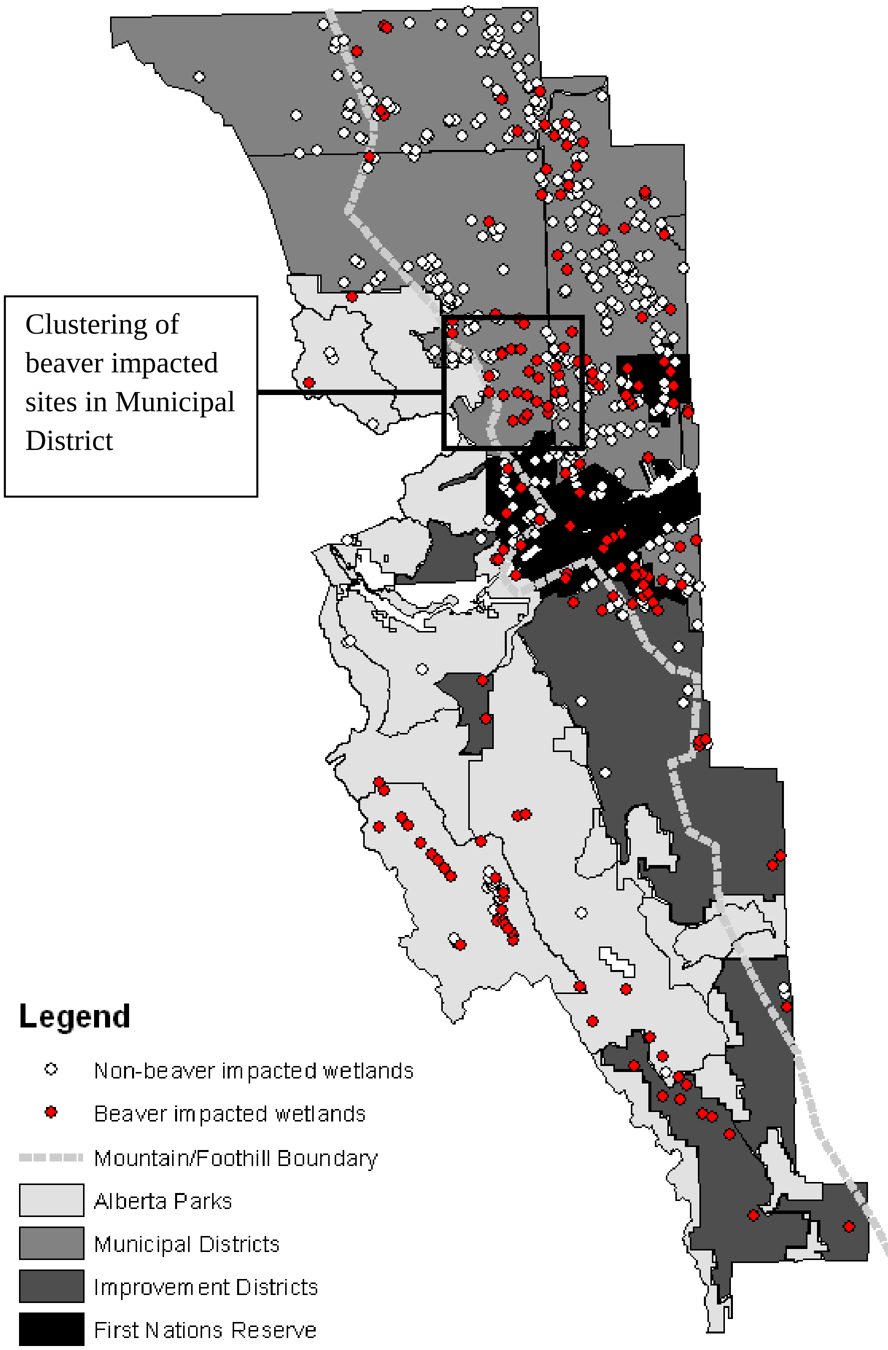


Fig. 13 – Distribution of beaver impacted and non-impacted wetlands

3.2. Distribution of peatlands and beaver impacted peatlands

Of the 529 wetlands inventoried with GIS, 81 were visited and soil samples taken from 79. Soil collection was not possible at two sites. Soil samples were taken and ignition tested to assess organic content (Fig. 14). Peat was found at 64% of these sites (see section 2.5 for definition of peat).

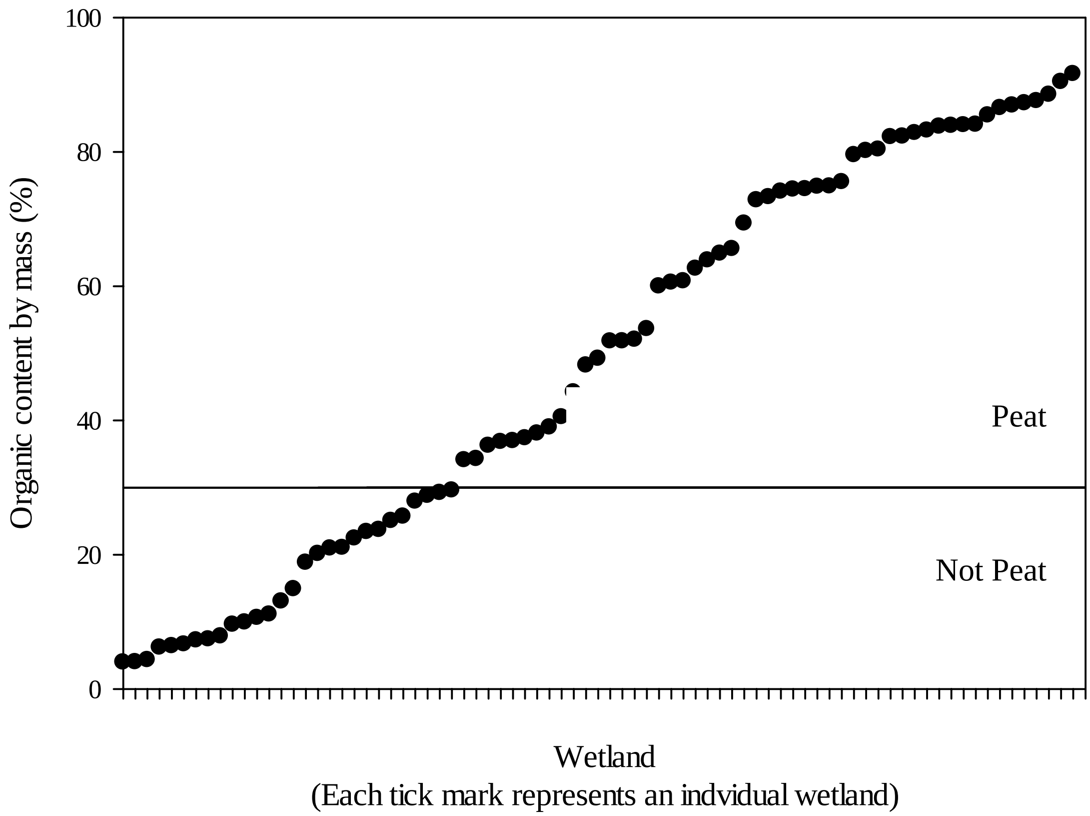


Fig. 14 - Results of soil ignition testing

There were differences in the percentage of wetlands found containing peat soils (Fig. 15) Proportionally fewer mountain wetlands were peatlands or peat-forming wetlands (peaty wetlands; 57%) than foothill ones (71%) (Table 5). The jurisdiction with the greatest proportion of peaty wetlands was the Municipal Districts (75%) followed by Alberta Parks (57%) and the Improvement Districts (56%) (Table 5). Unfortunately, data were not available for the First Nations Reserve land as access was not granted.

Table 5 - Distribution of peat-forming and non peat-forming wetlands

	Peat-forming		Non-peat forming		Total
	No.	%	No.	%	
Physiographic location					
Mountains	16	57	12	43	28
Foothills	36	71	15	29	51
Jurisdiction					
Alberta Parks	12	57	9	43	21
Municipal Districts	30	75	10	25	40
Improvement Districts	10	56	8	44	18

Evidence of past or present beaver activity was found at 69% of the peaty wetlands visited (Table 6). There appear to be regional and jurisdictional differences in beaver activity. In the mountain region, 100% of visited peaty wetlands had evidence of past or present beaver habitation whereas only 56% of those in the foothills did. All of the peaty wetlands visited in the Alberta Parks had evidence of beaver habitation whereas only 57% of those in the Municipal Districts did however, for this sample size the differences are not statistically significant ($p=0.27$, G-test). The inventory map shows some clustering of peatlands, again in the southwestern area of the Municipal Districts (Fig. 15).

Table 6 - Distribution of beaver impacted and non-impacted peat-forming wetlands

	Beaver impacted		Non-beaver impacted		Total
	No.	%	No.	%	
Physiographic location					
Mountains	16	100	0	0	16
Foothills	20	56	16	44	36
Jurisdiction					
Alberta Parks	12	100	0	0	12
Municipal Districts	17	57	13	43	30
Improvement Districts	7	70	3	30	10
Total					52

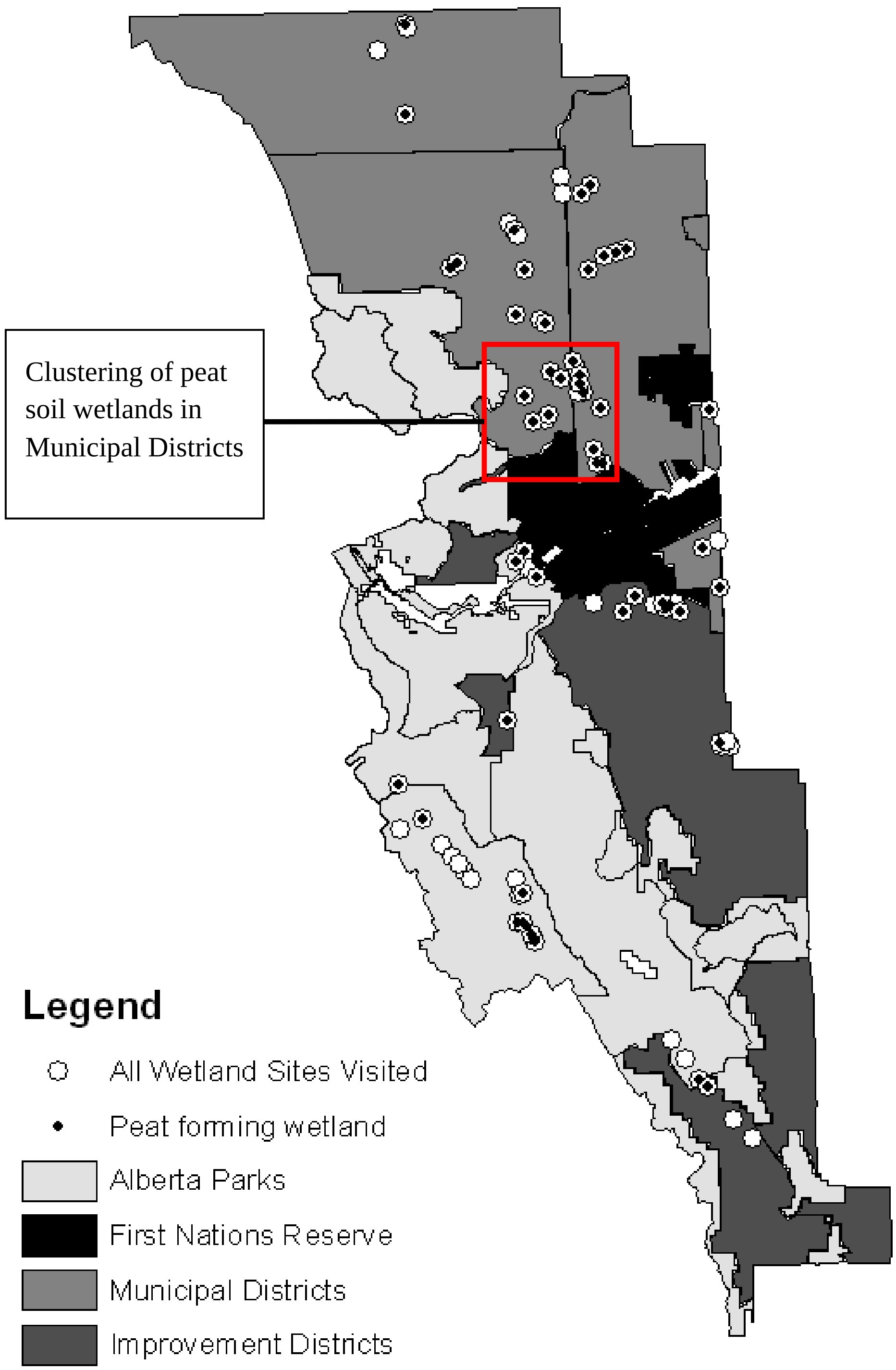


Fig. 15 - Distribution of peat-forming and non peat-forming wetlands

Of all of the beaver impacted wetlands visited, 59% were found to be peat forming (Table 7). In the mountains, this figure is 57% and the foothills it is 61%. For the jurisdictions, the proportions are 57% of Alberta Parks peatlands, 65% of Municipal District peatlands, and 50% of Improvement District peatlands. Again these differences are not statistically significant (p=0.63, G-test) although suggestive of an influence.

Table 7 – Beaver impacted wetlands which are peat forming

	Peat-forming		Non-peat forming		Total
	No.	**%**	**No.**	**%**	
Physiographic location					
Mountains	16	57	12	43	28
Foothills	20	61	13	18	33
Jurisdiction					
Alberta Parks	12	57	9	43	21
Municipal Districts	17	65	9	35	26
Improvement Districts	7	50	7	50	14

3.3. Area of open water in wetlands

Visual analysis of the 2007/08 aerial imagery showed 40% of the wetlands inventoried had areas of open water present (Table 8). Open water area on individual wetlands was measured using a GIS and varied greatly, ranging by four orders of magnitude (27 to 2.6 $x10^4$ m^2). The mean open water area per wetland was 1.5 m^2 $x10^3$.

Mean open water area per mountain wetland was almost double that of foothill wetlands. The total open water area in mountain region wetlands is approximately one third of that in the foothills region wetlands. Municipal district wetlands have a much lower mean open water area than other jurisdictions. Alberta Parks wetlands have almost three times the open water area as Municipal Districts and Improvement districts and First Nations Reserves wetlands have over five times the open water area as Municipal Districts. This is compared against a wetland size difference, between the mountains and the foothills, the latter being approximately 50% larger (Table 8). This difference is accentuated when comparing the Alberta Parks region and the Municipal Districts. Alberta Parks wetlands are almost half the size of Municipal District wetlands, but have almost three times the area of surface water.

Of the total wetland surface water area in the study area 17% is in the Alberta Parks jurisdiction, 36% in the Municipal Districts, 23% in the Improvement Districts and 24% in the First Nations Reserve. In the mountain region, open water area accounts for over one fifth of the total wetland area (Table 8). In the foothill region, this figure is less than one tenth. This coincides with patterns of beaver occupation, with a higher proportion of mountain wetlands impacted by beaver than in the foothills (Table 4). Jurisdictionally, open water in Municipal District wetlands accounts for one twentieth of total wetland area. In comparison, Alberta Parks, Municipal Districts and First Nations Reserves wetlands have open water covering at least one fifth of their area. It is noted that wetland areas were calculated using a wetland layer from the National Topographic Database (NTDB) that was produced in 1996, and therefore may lack accuracy. However, it is likely that in relation to each other, wetland areas will have remained in similar proportions between the two geographical regions and the four jurisdictional areas.

Table 8 - Number and distribution of wetlands with open water

	No. Wetlands	No. wetlands with open water	Total wetland area	Mean individual wetland area	Total open water area	Mean open water area	
Physiographic location			$m^2 \times 10^5$	$m^2 \times 10^5$	$m^2 \times 10^5$	$m^2 \times 10^3$	SE
Mountains	133	75	130.97	0.99	3.10	2.31	0.29
Foothills	396	135	604.42	1.50	4.85	1.22	0.21
Total	529	210	735.59	1.4	7.92	1.50	
Jurisdictional location							
Alberta Parks	59	42	42.68	0.83	1.38	2.27	0.43
Municipal Districts	361	106	556.35	1.52	2.88	0.80	0.13
Improvement Districts	42	25	56.04	1.23	1.81	4.30	1.27
First Nations Reserve	67	30	81.14	1.36	1.85	5.00	0.57
Total	529	210	735.59	1.4	7.92	1.50	

When wetland open water area is compared to beaver impacted wetlands (Table 9), those with beaver impact had much more open water than those without beaver impacts (3.9 vs. 0.4km^2 ; p < 0.001 Wilcoxon test).

Table 9 - Open water area on beaver impacted and non-impacted wetlands

	No. Wetlands	No. wetlands with open water	Mean open water area	SE	50% error
			m^2 x 10^3		
Beaver impacted	166	147	3.9	0.47	1.95
Non-beaver impacted	363	63	0.4	0.12	0.20
Total	529	210	1.5		

Comparison of wetland open water area between beaver impacted and non-impacted wetlands (Fig. 16a) shows the former had significantly more open water (p < 0.001 – Wilcoxon test) However, the accuracy of the analysis of open water extent was limited by the image resolution and the temporal span of image acquisition. But, even if a very conservative error value is used (50% is used as an example; Fig. 16b), there remains a clear difference in open water area between beaver impacted and non-impacted wetlands.

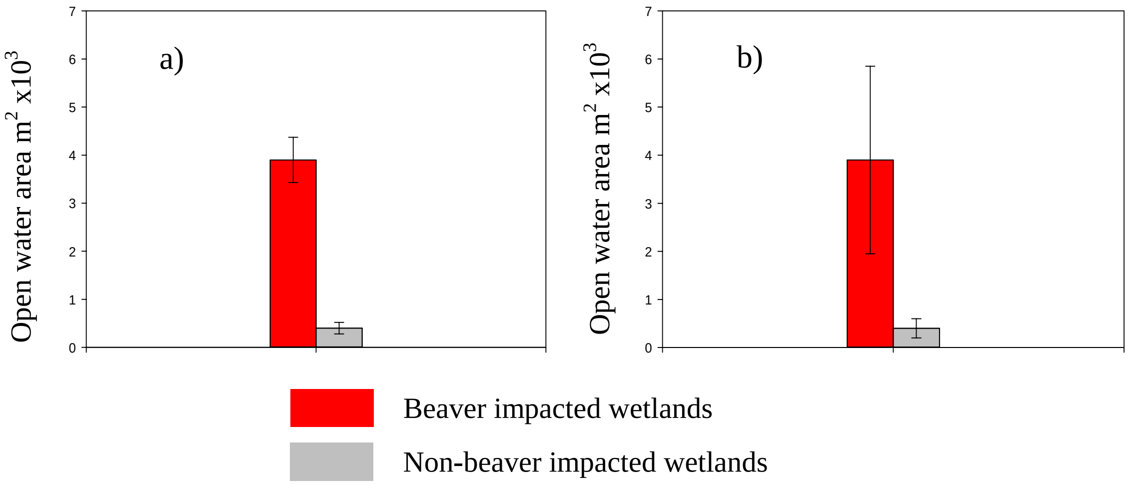


Fig. 16 - Impact of beaver on open water area in wetlands with a) standard error, and b) assumed 50% error

Number of open water features per wetland was also assessed (Table 10). Open water occurrence was approximately two and a half times higher on wetlands with beaver. On average, the number of individual open water features per wetland was almost 12 times greater on beaver impacted wetlands compared to non-impacted ones.

Table 10 - Mean pond numbers per wetland by study area location

	No. Wetlands	No. wetlands with open water	Total no. ponds	Mean no. ponds per wetland
Physiographic location				
Mountains	133	75	357	3
Foothills	396	135	580	1
Total	529	210	937	2
Jurisdiction				
Alberta Parks	59	42	160	3
Municipal Districts	361	106	368	1
Improvement Districts	42	25	201	5
First Nations Reserve	37	37	208	3
Total	529	210	937	2

3.4. Soil formations in mountain peatlands

3.4.1. Evidence of layering of wetlands

Ground Penetrating Radar (GPR) was used to investigate the sub-surface structure of peatlands. Depth penetration varied from 0.4 m to 2 m. The full thickness of soil was imaged at site 55, as the clay base was very shallow (0.4 m). In general, depth penetration was 1 to 1.2 m (Table 11).

Table 11 - Depth penetration of GPR and electrical conductivity (EC) of surface water

	GPR penetration depth		**Core depth to clay**		**Surface water EC**
Site number	**ns**	**m**	**Minimum**	**Maximum**	**µS/cm**
4	100	> 0.9	0.9	2.05	312
33	95	> 1.2	0.9	< 2.2	366
55	65	0.4	0	0.4	487
209	75	1	0.6	2.3	405
490	80	> 1.2	0.8	2.3	507
510	110	2	0.9	2.3	307
524	75	1.1	0.45	1.7	322
559	100	> 1	0.8	1.8	414
903	85	> 1	0.2	1.3	504

Previous research at Sibbald Research Wetland, site 33 in this study, showed that the peat matrix is interspersed with mineral material (Janzen and Westbrook, 2011). GPR data from nine peatlands, including site 33 were analysed to assess whether this was a common phenomenon. Of the 9 peatlands surveyed, 8 had evidence of mineral material interwoven within a peat matrix (Table 12) of these 8, all showed this evidence in both soil cores and GPR traces. However, the spatial extent of layering varied greatly among sites.

Table 12 - Evidence of soil layering in wetlands

	Site location		Core evidence?	# cores showing layering/ total cores	GPR evidence?	# GPR transects showing layering/ total transects
Site no.	**Geophysical***	**Jurisdictional****	**(Y/N)**		**(Y/N)**	
4	M	AP	Y	1/7	N	0/2
33	M	ID	Y	16/17	Y	9/10
55	F	MD	N	0/8	N	0/3
209	F	MD	Y	6/7	Y	2/2
490	F	MD	Y	5/12	Y	4/4
510	F	ID	N	3/9	Y	1/2
524	M	AP	Y	10/12	Y	1/4
559	M	AP	Y	8/12	Y	2/3
903	M	AP	Y	8/12	Y	8/11

* M = Mountains, F = Foothills

**AP = Alberta Parks, MD = Municipal Districts, ID = Improvement Districts

Soil profiles for many of the wetlands surveyed were complex. Cores often indicated a gradual change from organic to mineral material, with no defined boundary between the two. In other cases there were gradual changes in mineral content within the organic soil, but still remained a mixture of organic and mineral material. These fuzzy boundaries between materials affected the clarity, and thus interpretability of the GPR images; gradual changes in soil properties provide less clear radar reflections. The most conclusive GPR images are those from sites 33 and 903, and results from these surveys at these two wetlands are presented in the following two sub-sections as examples. The full soil core and GPR record of all 9 surveyed wetlands are provided in Appendix C.

It was possible to show an upper layer of peat at 8 of 9 sites where at least one soil core was interrupted by a mineral layer (Table 13). The linear extent of these mineral layers has been estimated as the longest continuous contact between coring points shown on the GPR transect traces. This length ranged from between 0 m and 10 m, to between 60 m and 80 m.

Table 13 - Mean peat thicknesses and mineral layer thicknesses

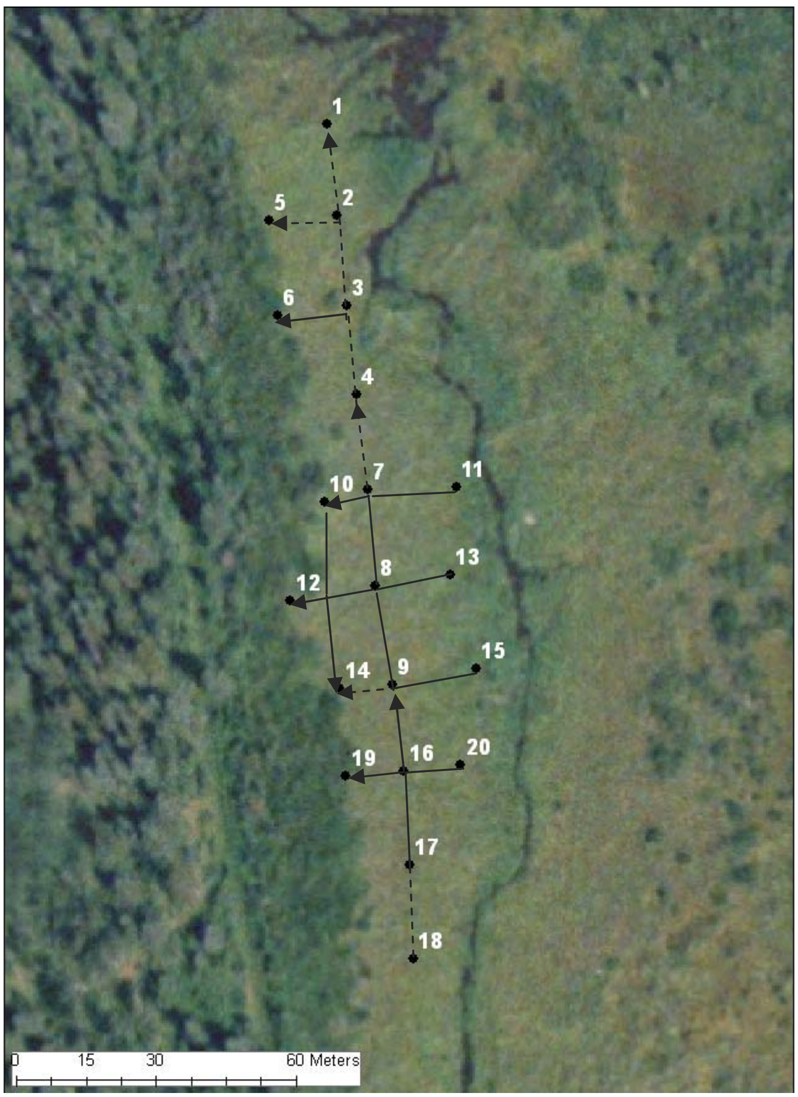
Site number	Upper layer peat thickness m	Total peat thickness m	Mean Mineral layer thickness m (# of measurements)	Mineral layer linear extent m
4	0.90 - 1.20	0.9 - 1.80	0.2 (1)	> 0 to < 10
33	0.40- 2.00	0.40 - 2.20	0.35 (9)	> 60 to < 80
55	0 - 0.60	0 - 0.60	N/A	N/A
209	0.10 - 1.05	0.10 - 2.15	0.50 (2)	> 10 to < 20
490*	0.40 - 0.95	0.40 - 1.10	0.17 (3)	> 10 to < 20
			0.45 (2)	> 10
510	0.90 - 1.95	0.90 - 2.10	N/A	N/A
524*	0.15 - 0.35	0.15 - 0.55	0.43 (7)	> 50
			0.64 (5)	> 40
559*	0 - 0.50	0 - 0.50	0.37 (2)	> 10 to < 20
			0.12 (2)	> 10 to < 20
903	0 - 0.85	0 - 1.05	0.16 (6)	> 50

* It was possible to estimate for more than one mineral layer at these sites

The partial areal extent of mineral layers in site 33 and 903 can also be estimated through cross-referencing of the soil core and GPR data. This is discussed in the following sections (Sections 3.4.2 and 3.4.3).

3.4.2. GPR survey - Site 33

Site 33 is known to have extensive mineral material which is underlain and overlain by peat (Janzen and Westbrook, 2011). GPR surveys were conducted in the same area where the layering was found. Penetration depth was less than 1.2 m with a soil thickness to the clay boundary of over 2 m. The traces show the buried mineral layer was continuous in places and discontinuous in others (Fig. 17). The GPR traces (Figs. 18 and 19) show the complexity of the peatland subsurface.



Key

Continuous mineral layer

Discontinuous mineral layer

Transect order

T1 – 4,3,2,1

T2 – 2,5

T3 – 3,6

T4 – 9,8,7,4

T5 – 11,7,10

T6 – 14,12,10

T7 – 13,8,12

T8 – 15,9,14

T9 – 18,17,16,9

T10 – 20,16,19

Fig. 17 - Site 33 transect layout and mineral layer extent

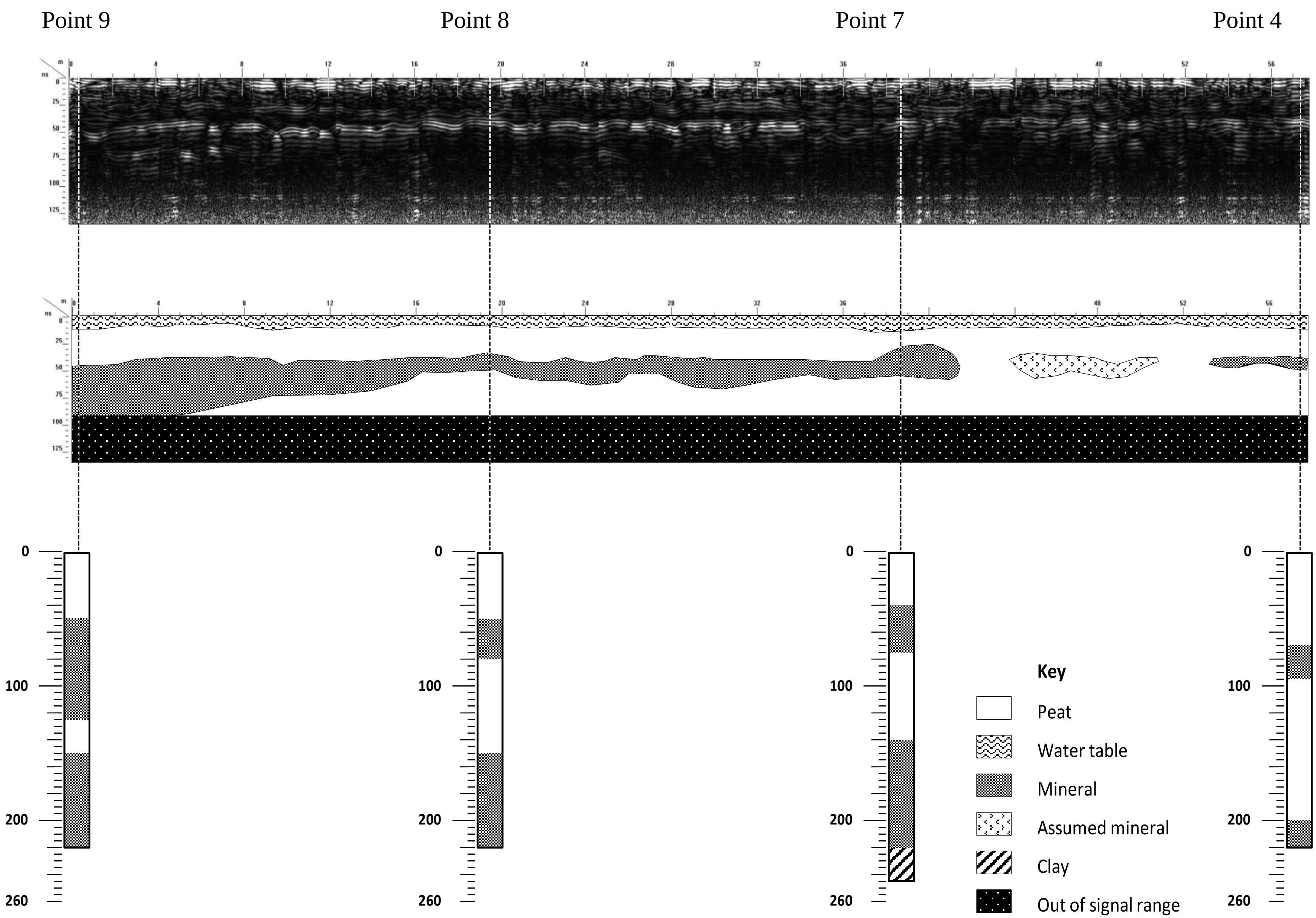


Fig. 18 – Site 33, transect 4. GPR and soil core interpretation

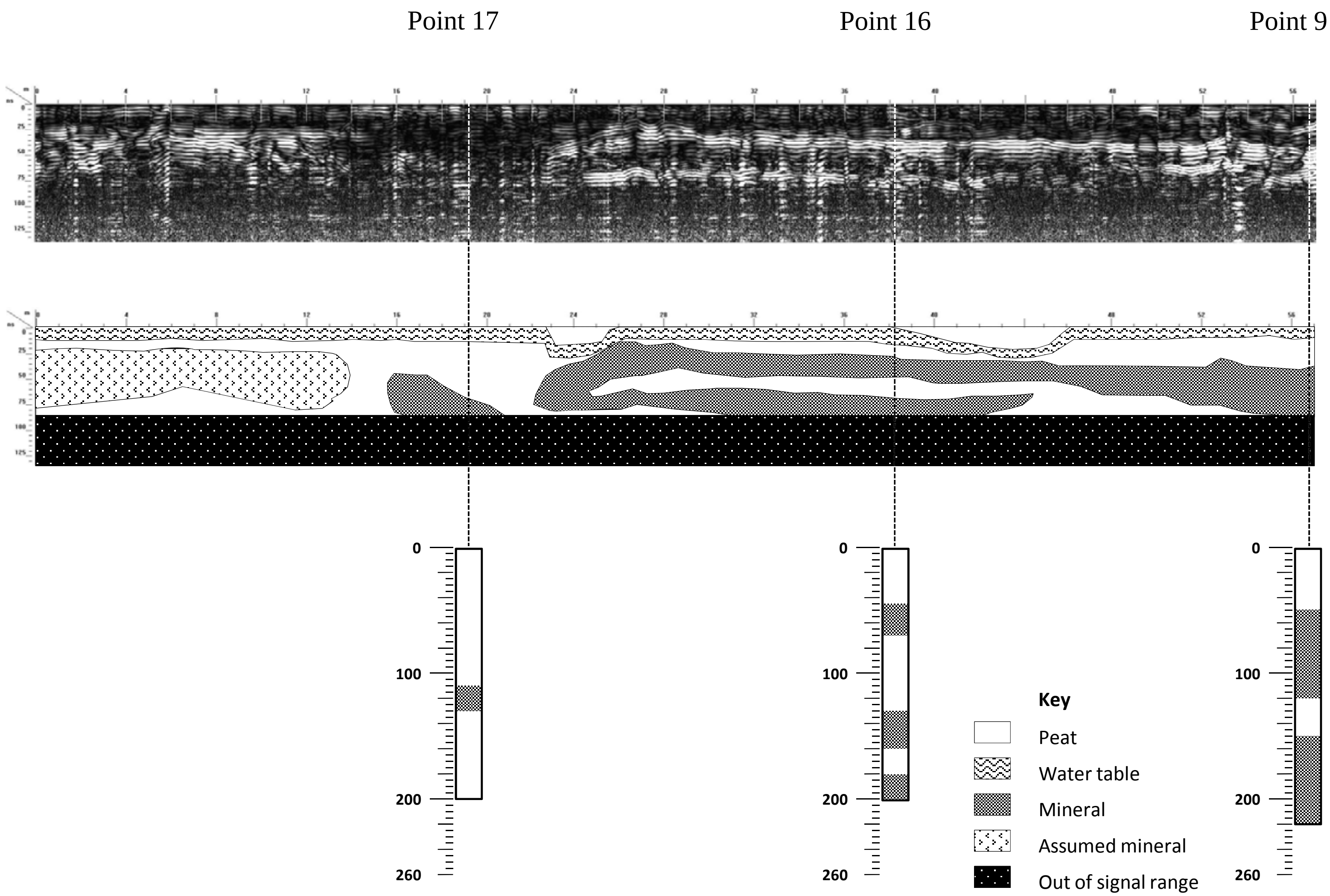


Fig. 19– Site 33, transect 9. GPR and soil core interpretation

There is evidence of several individual mineral layers. One large layer was identified between point 7 and point 17 (north-south), which also extended laterally east-west (see Fig. 17). The upper boundary of this layer was found to vary between 40 cm and 70 cm below the peat surface. The mineral layer thickness was varied between 10 cm and 60 cm. The thickness of the mineral layer at each point is illustrated in Fig. 20.

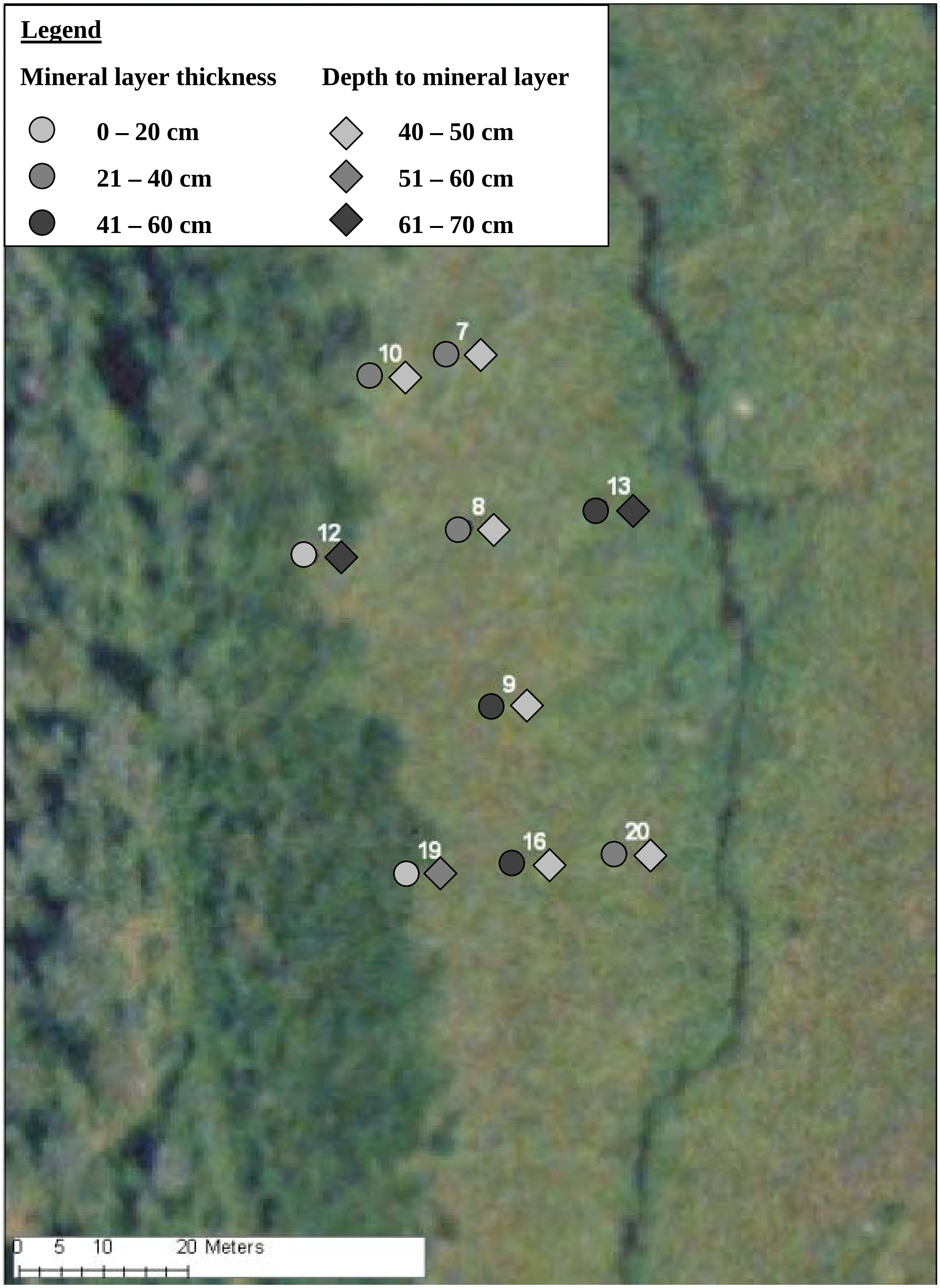


Fig. 20 - Thickness of mineral layer, and depth from the surface to that layer, site 33

3.4.3. Site 903

Site 903 also has a clear layer of mineral material within the peat matrix. Over much of the area surveyed, the mineral layer is discontinuous (Fig. 21). Radar penetration depth was less than 1 m with a maximum and minimum soil depth to the clay boundary of 0.2 m to 1.3 m, respectively. The minimum depth to clay was found at the edge of the wetland, at point 11. The GPR traces (Fig. 22 and 23) show the buried mineral layer was continuous in places and discontinuous in others (Fig. 23). As with site 33, there is considerable complexity in the subsurface of the wetland.

Key		Transect order		
———	Continuous peat/ mineral layering	T1a – 1,2,3,4,5	T4 – 13,6,14	T8 – 19,10
– – –	Discontinuous peat/ mineral layering	T1b – 5,6,7,8	T5 – 15,4,16	T9 – 20,21,22
………	No peat/mineral layering	T2 – 9,10,11	T6 – 17,2,18	T10 – 23,21,24
		T3 – 7,12	T7 – 9,17	T11 – 25,26

Fig. 21 – Site 903 layout and interpretation of soil core points and GPR transects

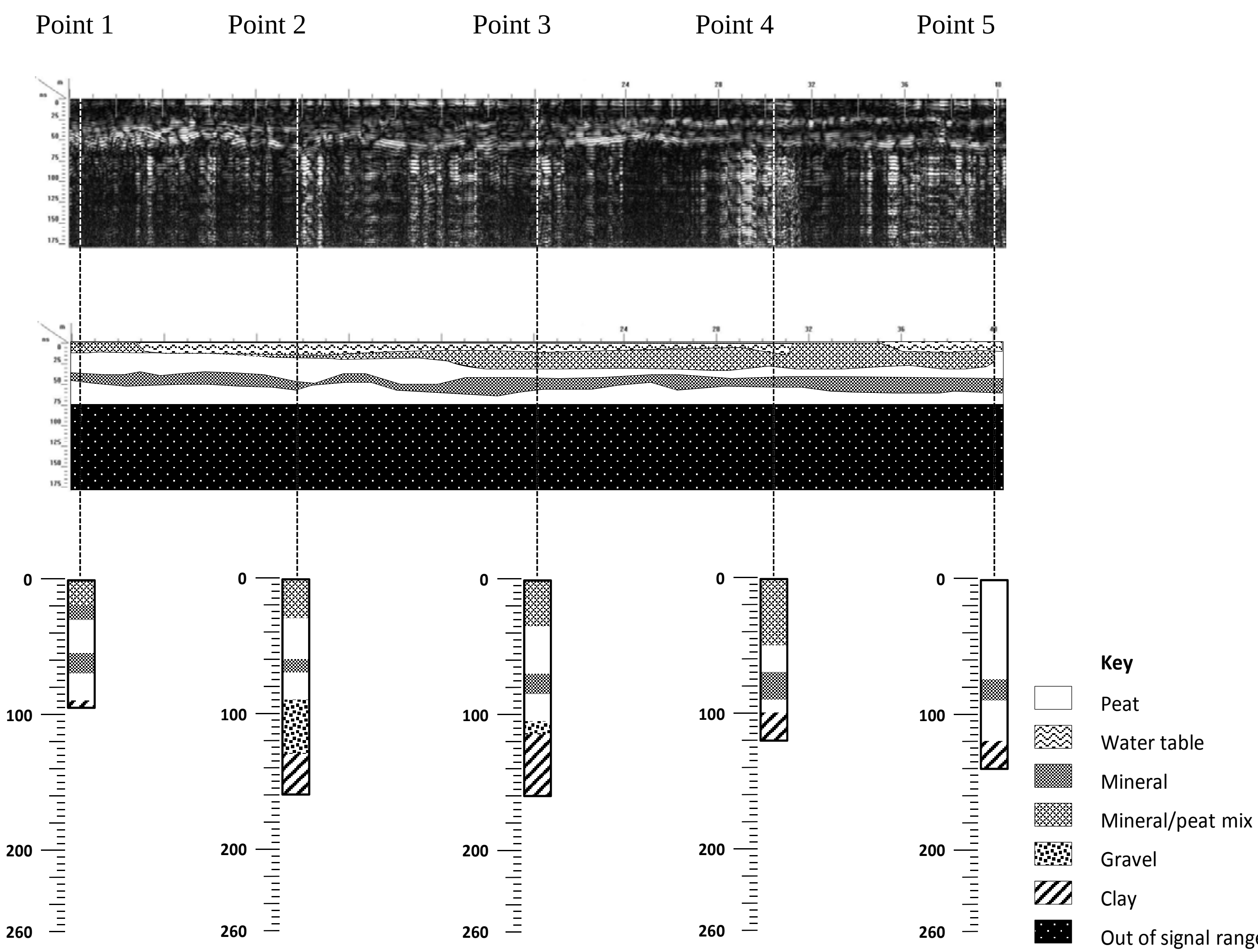


Fig. 22 – Site 903 transect 1a GPR and soil core interpretation

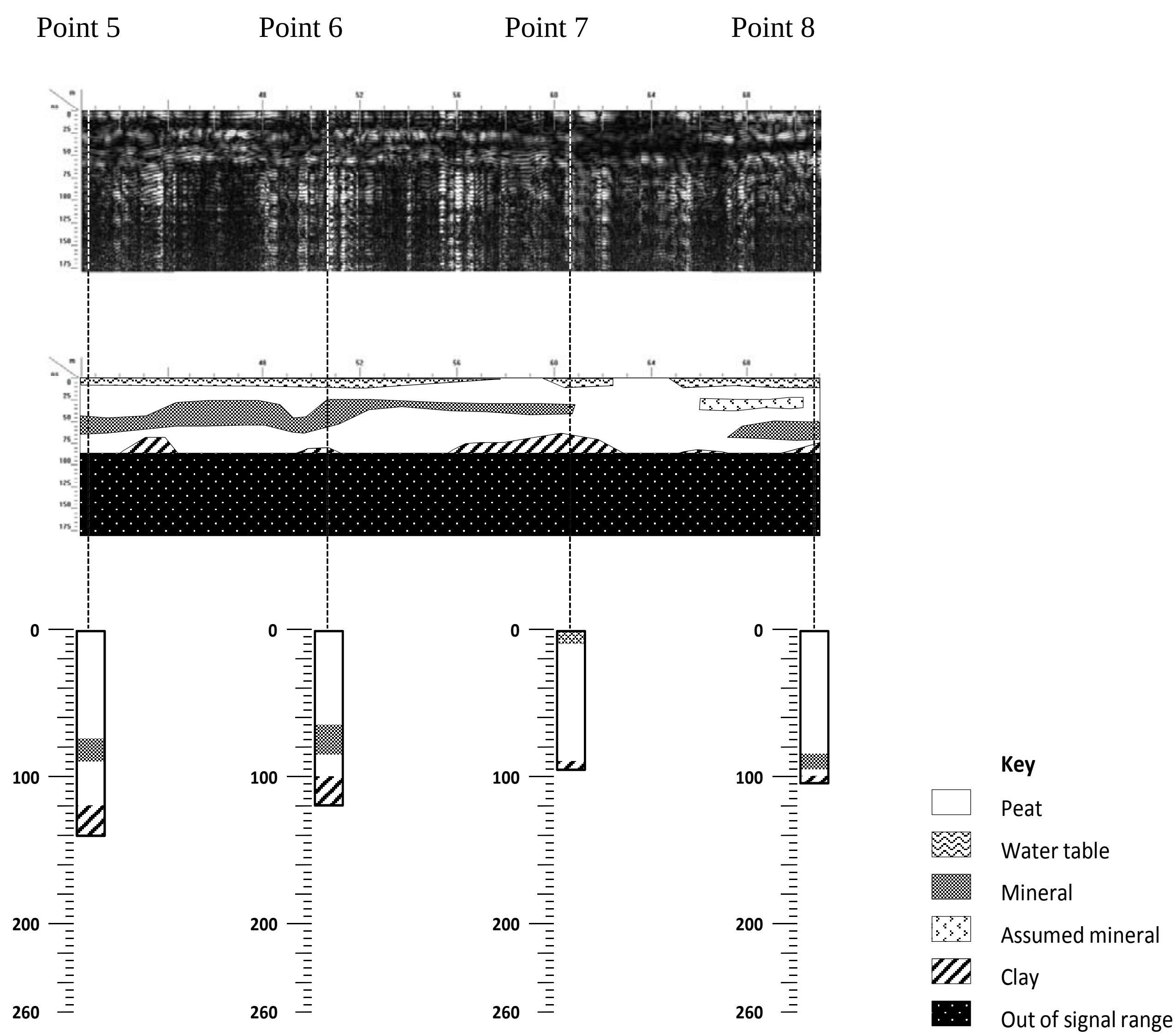


Fig. 23– Site 903 transect 1b GPR and soil core interpretation

There is evidence of a mineral layer at this site, and possible evidence that a new one is forming. The near surface of the peatland has peat soil with a high mineral content and mineral material sitting on parts of the wetland surface where there is currently a beaver pond (Fig. 24).

Fig. 24 - Core photo (top) with background showing mineral material on the wetland surface, and photo (bottom) showing mineral material on the soil surface of a shallow pool

The sub-surface layer was identified between points 1 and point 6 (see Fig. 21). Although it was not possible to complete a continuous set of transects to point 26, it looks likely that this layer extends at least to that point (full transect interpretations in Appendix C). There was some lateral extension from this transect, shown by points 15 and 16. The thickness of this layer was near the limit of the GPR resolution, and therefore may be more laterally spread than indicated. However, the coring strategy was not sufficient to confirm this. The upper boundary of this mineral layer varied between 55 cm and 75 cm below the peat surface. The mineral layer thickness was found to vary between 10 cm and 20 cm. The thickness of the mineral layer at each point from 1 to 6 is illustrated in Fig. 25.

Fig. 25 - Thickness of mineral layer and depth from the surface to that layer, site 903

4. DISCUSSION

4.1. Wetland, peatland and beaver pond distribution

This study infers that beaver distribution in wetlands varies across the study area as a result of both anthropogenic and physiographic influences. Anthropogenic influences include wildlife management policies and land use, and physiographic influence relates to difference in the availability of habitat between the two distinct regions studied (the foothills and the mountains). The distribution of peatlands was also described. They are present across the whole of the study area, and are more common in the lower elevation, lower gradient regions. Also documented was the influence of beaver on one hydrological variable; wetlands inhabited by beaver had greatly enhanced open water area.

In the greater Kananaskis region of Alberta, wetlands occur from elevations of 1215 m up to 2194 m, at a density of 0.07 km^{-2}; two thirds of these located in the foothills. Their distribution reflects the physiography of the landscape. In the mountain region, wetlands are restricted to the major mountain valleys, particularly the Spray Lakes valley, the upper part of the Kananaskis valley and the Highwood valley. Wetlands are common in valley bottoms because this physiographic position lends itself to a convergence of flow paths that can maintain wet conditions at the near-surface (Cole et al., 1997). In the foothills region, wetlands also occur in low-lying positions, but these are more evenly distributed because of the rolling topography. Where the topography was steep in the foothills region, there was a lower density of wetlands.

Although 529 wetlands were identified in this inventory, it is likely that there are more wetlands in the study region. The wetland GIS layer used was published by Natural Resources Canada in 2007, with data gathered between 1972 and 1996. The metadata for the layer does not describe the method by which it was produced, so the wetland layer was manually cross checked with the aerial images to ensure that it did coincide with apparent wetland features. Ground-truthing also provided a physical check of a sample of these wetlands. Although the ground-truthing showed that the GIS layer accurately identifies wetlands, field observations during fieldwork suggest that there are a number of wetlands present which were not captured by the baseline NTDB GIS data layer. There are likely several reasons for this: i) they may have developed after the GIS layer was produced; ii) they may have been too small for the original analysis method to detect; or iii) they may have been obscured by trees or snow cover on the imagery used to develop the GIS layer. Technology has developed since the GIS layer was created, which has improved the ability to remotely sense wetlands (Halabisky et al., 2013). LiDAR can be used to detect wetlands, even under forest canopy (Lang and McCarty, 2009), for example, a 1 m LiDAR based DEM improved the accuracy of the manual wetland inventory in the United States by 25% (Maxa and Bolstad 2009). Since LiDAR was unavailable for the entire study area, aerial images were analysed both with and without the wetland baseline data to ensure the inventory was as robust as possible. When LiDAR becomes available for the region, wetland mapping should be repeated to ensure this important ecological resource is properly inventoried (Finlayson et al., 1999).

This study provides a detailed estimate of the distribution of individual peatlands in the southern Canadian Rockies. This complements Halsey's (1997) provincial peatland inventory which describes peatland distribution as a function of percentage land cover, by providing finer detail. It also complements Zoltai et al.'s (2000) inventory of wetlands across Canada, by focusing on a specific region and physiographic setting. This study identified 52 peatlands or peat forming wetlands, representing approximately 64% of the wetlands in the study area. If it could be inferred that this is the percentage across the entire study area, then of the 529 wetlands identified, approximately 338 would be peatlands. The United States Department of Agriculture (USDA) produced a summary of studied peatlands in the Rocky Mountains in the northern United States (USDA, 1998). Their report synthesised a number research papers, detailing what is known about peatlands and their ecology in this region. In total, 61 peatlands and their value in terms of biodiversity were documented across the Rocky Mountain regions of four states (Idaho, Washington, Montana and Wyoming). If the ecological value of peatlands in the USDA report is similar to those in the greater Kananaskis region, then this suggests that the near 350 peatlands in the 7912 km^2 study area represent a substantial natural resource. Given the size of the study area compared to the extent of this ecozone, these peatlands are likely to represent a small fraction of the overall resource in the Canadian Rockies.

Wetland (both organic and mineral based) disturbance by beaver was shown to vary by physiographic location and jurisdiction. Even though there were fewer wetlands in the mountain region, beaver impacts were twice as likely to be found there than in the foothills region. This is most likely due to the differing priorities of the main landowners/custodians in each jurisdiction.

The mountain area consists primarily of improvement districts and provincial parks whereas the foothills region consists primarily of Municipal Districts and a First Nations Reserve. None of these jurisdictions have an official published policy on beaver management. Provincially though, there is a quota system to limit the number of beaver removed from the land. The Government of Alberta (2012) reports that the 2008-2012 average beaver pelt harvest was 12,075. Trapping may thus be the cause of the low proportion of wetlands (20%) in the Municipal Districts found to have beaver ponds. Further, the major land uses in the Municipal Districts include ranching and forestry. Beaver are likely to be perceived as a nuisance to these two industries (Bhat 1993; Conover, 1994; Messmer, 2000; Tornblom, 2011), and the pelt harvest rates suggest that beaver are actively being removed from the landscape. In the Improvement Districts, the proportion of beaver impacted wetlands is 40% higher than the Municipal Districts. This jurisdiction does not have the forestry or ranching found in the Municipal Districts. As well, this jurisdiction contains some wildlife protection areas that are mostly used for recreational purposes. Thus beaver are more likely to be tolerated as they are not directly impacting peoples' livelihoods. Indeed, in many cases their presence could be seen as beneficial. For example, beaver ponds are known to provide good conditions for fishing, and wildlife viewing – beaver ponds attract a plethora of other wildlife (Conover, 2011). Other factors that may be important in influencing beaver populations in the study area are availability of food and concentration of predators. For example, the interaction of predators such as wolves, and prey, such as beaver and elk can be complex (Hebblewhite et al., 2005). Wolves will prey on beaver, but also on elk. The herbivory of elk can reduce the available food source for beaver (Wolff et al., 2007), but the predation of wolves on elk reduces this impact (Hebblewhite et al., 2005). Wolf distributions are also influenced by human factors, being discouraged from living in areas of high human population (Hebblewhite et al., 2005). So it can be seen that humans are not the sole influence on beaver colonisation patterns and there are likely to be other indirect human influences through other wildlife interactions.

The Alberta Parks jurisdiction had a similar proportion of wetlands impacted by beaver as the Improvement Districts. There are stringent rules on development, high levels of wildlife protection in the park area, and an unofficial policy to adapt park management practices to allow co-existence with beaver, which indicates to remove them only when absolutely necessary to protect infrastructure (M. Percy of Alberta Parks, pers. comm.). That there was a similar proportion of inhabited wetlands in the parks and Improvement Districts may indicate that the suitable wetland habitat in both jurisdictions is already colonised, and that land management and land use practices in the Improvement Districts are sufficient to protect beaver populations. The similarity is perhaps surprising as logging and seasonal grazing does occur in the Improvement Districts. It may be that licensing of these activities provides adequate protection of beaver, compared to logging and ranching practices on private land, but further study is needed.

Interestingly, the proportion of the First Nations Reserve wetlands with evidence of beaver activities (40%) fell almost exactly halfway in between that of the protected regions and the Municipal Districts. Beaver management policy is decided at the Reserve level, and was not publically available for the Stoney Nakoda First Nation. But what can be concluded from the data is that the way the reserve manages beaver is clearly different from that of the other studied jurisdictions. Berkes (1998) reports that the Cree First Nation in the eastern sub-Arctic region of Canada manages their beaver to a population level such that their food source is sustainable. This differs from the management practices used in the non-First Nations jurisdictions, which tend to focus on protection of beaver or population management by quota. Physiographically, the Stoney Nakoda Reserve sits in the foothills, and so should be more densely impacted by beaver than the Municipal Districts. Without understanding more about the way it is managed, it is difficult to draw specific conclusions. Such understanding though may help other jurisdictions develop beaver management policies that provide a balance of protection of both beaver and human interests while retaining and increasing ecosystem services provided by beaver-maintained wetlands (Tornblom et al., 2011).

Although the Municipal Districts generally had a low density of beaver impacted wetlands, there was a high density cluster of beaver impacted wetlands in one Municipal District, coincident with the Ghost Valley Forest Recreation Area (GVFRA). Land use in GVFRA is restricted to recreation activities such as ATV trails and fishing. This land was an Improvement District until 1988, as reported by the Provincial government (Alberta Municipal Affairs, 2013). Interestingly, the average distance from each wetland to the road was higher within this cluster (average of just over 3 km) than for other wetlands in the Municipal District (average of 1.5 km). High road density fragments habitats and increases beaver mortality through road kills (Formann et al., 1997; Gunther et al. 1998). This finding suggests that the proportion of wetlands impacted by beaver can be changed through modifying management practices. If management practices are designed in a way that increases beaver impact on wetlands, this is likely to help towards balancing human interests with the improvement of wetland related ecosystem services (Tornblom et al., 2011).

Peatlands appear to be good beaver habitat as 59% of the beaver impacted wetlands studied are peatlands. The proportion of beaver inhabited peatlands contradicts descriptions from the literature of peatlands as marginal habitat (Rebertus, 1986; Pastor et al, 1993). But, few studies quantify the evidence of beaver habitation of peatlands, and so this assertion may be based on anecdotal rather than scientific evidence. Studies centred on peatlands have shown that beaver commonly inhabit them. Milbrath (2013) describes beaver colonisation patterns in 9 peatlands in the Rocky Mountain foothills of Montana. As well, Rebertus (1986), who concluded that peatlands were marginal habitat, in fact found that 42% of peatlands in his North Central Minnesota study site had evidence of beaver impact. Further, researchers studying other peatland attributes have noted the presence of beaver at their study sites (Yavitt et al, 1990; Roulet et al., 1997; Turetsky and St. Louis, 2006). At a continental scale, Gorham et al. (2007) showed that there is evidence of beaver in peatlands across much of North America throughout the Holocene. This suggests that left undisturbed, beaver readily colonise peatlands. It would be interesting to revisit Rebertus' study site to determine if more (or fewer) peatlands have been colonised by beaver since his study given that Johnston and Naiman (1990) reported that the rate of pond creation after the first two decades of beaver re-colonization of a landscape becomes limited by lack of geomorphically suitable habitat.

Interestingly, and in contrast to the results for wetlands, the proportion of beaver inhabited wetlands that are peatlands is very similar across the 3 jurisdictions: Alberta Parks – 57%, Municipal Districts 65% and Improvement Districts - 50%. This may be an artifact of the sampling design but, equally it may be that socioeconomic forces are not shaping beaver inhabitation of peatlands but are in mineral based wetlands. Peatlands are often drained for agricultural activities in places like Montana (Milbrath, 2013). Although this does occur throughout the Province of Alberta (Wilson et al., 2001), ranching, not cropping is the main land use activity in the Municipal Districts.

The inventory of wetlands, peatlands and beaver impacts presented herein represents a snapshot in time (2007 and 2008). However, understanding their importance and function in the landscape, both historically and presently, is important. Beaver, as ecological engineers, create and maintain wetland habitat (Westbrook et al., 2006) well suited to flora and fauna that benefit from open water like amphibians, waterfowl, fish, invertebrates and foraging ungulates (Naiman et al, 1986; Terwilliger and Pastor, 1999; McKinstry et al, 2001; Stevens et al, 2006; Wolff et al, 2007; Conover, 2011). As there is neither documentation of changes in wetland distribution over the time nor knowledge on the rate of beaver population expansion in the area following the height of the fur trade, it is difficult to know what level of impact beaver re-colonisation has had on the wetlands in the region since the population started to recover. Without this information it is difficult to predict the long term habitation of wetlands in the region by beaver.

One hydrological impact of beaver on wetlands in the study area was the great enhancement of open water area. There is a strong suggestion in the results that human activity is affecting the open water area on wetlands in the Municipal Districts. Municipal District wetlands are cover, on average, 50% more area than those in Alberta Parks (representing the difference in physical setting). However, the mean area of surface water on Alberta Parks wetlands is almost three times that of Municipal District wetlands. Although beaver are known to create open water area in peatlands (Johnston et al., 1990), only infrequently is the area quantified. Fewer studies have linked this change to peatland ecological and hydrological functioning. For example, Milbrath (2013) used aerial images of 9 peatland sites covering a period of 72 years showed that beaver presence increased the number of open water features. Although beaver also increase open water area in riverine systems by turning lotic into lentic habitat (Johnston and Naiman, 1987; Gurnell, 1998), the changes incurred to peatlands are likely quite different. Although they did not study beaver ponds, Tardif et al. (2009) showed that the creation of open water pools in peatlands changed their hydrological response to rainfall events in ways dependent on the shape and location of the pools. Two fens with equal open water to fen area ratio were compared in terms of run-off and found to be different as a result of their structural composition (tardiff et al., 2009). Whether beaver ponds have similar impacts on runoff generation in peatlands remains unknown.

Open water areas of peatlands have distinctly different biogeochemistry than non-open water areas. For example, water table dynamics, modifications of flow paths and wetness influence carbon (C) sequestration and release (Belyea and Malmer, 2004; Strack et al, 2005; Ise et al, 2008). Measurements of rates of carbon release from beaver ponds have been restricted to mainly peatlands in the boreal forest. For example Roulet et al. (1997) reported a C flux from a beaver pond in a boreal peatland as more than 200 g $Cm^{-2}y^{-1}$ and Crill et al. (1988) found that methane flux from an open peat bog was 107 g Cm^{-2} y^{-1}. At a continental scale, Whitfield et al. (submitted) suggests that resurgent beaver populations represent a significant source of atmospheric greenhouse gas due to the increase in ponding (up to 18% of oceanic emissions). Given the differences in the climate and peatland forms present in the Canadian Rockies as compared to the boreal forest, along with the high beaver occupation rates documented here, investigations of C dynamics in Rocky Mountain peatlands, as affected by beaver, are warranted.

The long term impacts of beaver on peatland morphology and ecology are not known. How beaver dams breach and the plant community recovers in peatlands is not well described in the literature. In peatlands, beaver create ponds by excavating peat and damming seepage (Mitchell and Niering, 1993). This means that dams in peatlands are less prone to washout than those in riverine environments due to the lower energy involved with the flowing water (Ray et al., 2001). As a result it is difficult to determine how long pond features have been, or will remain on the landscape, given the slow growth of peat (Charman, 2002). Westbrook et al. (2013) hypothesized that beaver ponds in peatlands could remain in a stable state for centuries. The current model for conceptualizing the effects of beavers on landscapes is the beaver meadow formation theory (Westbrook et al., 2011; Polvi and Wohl, 2012). However, it does not fully capture the effects beaver have on pre-existing wetlands and should thus be revised to encompass the fundamentally distinct hydrogeomorphic effects that occur when beaver build dams in peatlands.

4.2. Peatland sub-surface complexity

Results from soil coring and GPR surveys of nine wetlands show that many of the mountain peatlands studied have some level of mineral intrusion. In some cases this takes the form of defined mineral layers interwoven with peat, whereas in others it takes the form of peat containing substantial amounts of mineral material. Four out of the nine peatlands surveyed showed strong evidence of these mineral soil layers, and another two showed moderate evidence. Complex stratigraphy may thus be a common feature of peatlands in mountain environments. Such complex stratigraphy in peatlands, and its impact on their function is not widely discussed in the literature. Research into function has mainly focused on peatlands with continuous organic soils throughout their depth (e.g., Bragg, 2001; Holden, 2008).

GPR proved a useful tool for investigating the subsurface complexity. However, depth penetration was lower than reported in other peatlands studies. For example, Lowry et al. (2006) summarised reported values from three peatland sites surveyed by GPR to depths ranging from 12 m to 35 m to have ECs from 18 to 77 µS/cm. Measurements of the EC surface water of the peatlands studied herein (307 – 507 µS/cm), which were taken in a wet year, indicate that they have a relatively high EC. Depth of signal penetration might have been reduced by the high EC (Oelhoeft, 2000).). The complexity of the peatlands themselves may also contribute to the poor depth penetration as every reflection results in signal attenuation (Jol, 1995). This attenuation due to complex soil structure has been noted by experienced GPR users (Fisher, 2013).

The subsurface complexity observed in the studied peatlands may be a result of the sensitivity of mountain systems to environmental change. Mountain systems are temporally and spatially dynamic as elevation greatly affects temperature and climate (Benistoun, 2003), which drive ecological processes. Mountain zones contain geospatial boundaries, controlled by climate, which represent the physical limits of where different plant communities can exist. Relatively small changes in temperature can result in relatively large changes of plant communities over an altitude range. Therefore the vegetation composition in these regions is particularly sensitive to smaller temperature changes that might not significantly affect more stable ecologies (Theurillat and Guisan, 2001). Similarly, snowpack and snowmelt are greatly influenced by small temperature differences in mountain regions, affecting the timing, spatial extent and volume of surface and groundwater flow (Pomeroy et al., 2004). Therefore in a mountain region, changes in climate or major environmental events can result in exaggerated changes in hydrology, biogeochemistry, and ecology. For example, peatland vegetation may change from predominantly sedges to predominantly mosses as a result of a change in climate, or a layer of ash may be deposited in peatlands during major volcanic eruptions (Pyne-O’Donnel et al., 2012; Loisel et al., 2013). It is their position in this landscape that makes peatlands excellent archives of environmental change (Charman 2002; Lamentowicz et al., 2010; Chiverrell and Jakob, 2013).

The subsurface heterogeneity observed in peatlands of the greater Kananaskis area suggests that they have seen several major environmental changes since their inception. For example, the peat type at the Sibbald wetland (site 33) changes from moss-derived at depth to sedge-derived near the surface. At some places in the peatland, this change from moss to sedge peat is interrupted by a layer of mineral material. Radiocarbon dating of the peat above and below this mineral material indicates it was laid down between 6880 and 4110 years B.P. (Janzen and Westbrook, 2011). Field observations (A. Bedard-Haughn, pers. comm.) of the material are consistent with that of Mazama ash, which has been documented throughout the region (Oetelaar, 2002), including in other peatlands (Zoltai, 1988). The change in peat type could indicate a shift in climatic conditions or a change in system hydrology after the ash deposition. Deposition of ash in peatlands is an example of regional scale change.

At the more local scale, extreme events such as storms, severe fires, and large landslides contribute to geomorphic change in mountain environments (Chiverrell and Jakob, 2013). Extreme events can increase the delivery of mineral sediment from mountain slopes to valley bottoms where peatlands tend to be located. One such extreme event occurred June 20-22, 2013 when between 200 and 250 mm of rain fell in the Kananaskis region (Government of Alberta). There was widespread slope failure resulting in debris flows and the cutting of new stream channels (Star Phoenix, June 24, 2013). Some of the greatest rainfall totals were in the Highwood Valley area where a high-density of beaver affected peatlands was found during this study. Given the position of these peatlands on valley floors, it is likely that many were buried, at least partially, by mineral materials. No field observations have been made yet as the continuing unstable conditions and severe road washouts have kept the area closed to the public. Documenting the effect of this extreme rainfall event on peatland form would be an interesting research avenue.

Beaver are an ecological factor that can cause geomorphic changes to peatlands, given their effects on riverine systems (Gurnell, 1998; Corenblit et al., 2008). Studies of the geomorphic role of beaver in alluvial Rocky Mountain river valleys suggest that over millennia, beaver can interbed layers of fine sediment throughout the surficial profile (Kramer et al., 2012; Polvi and

Wohl, 2012). Reports of the geomorphic effects of beaver on peatlands are generally focused on surface activity, such as pond creation and excavation of canals (Westbrook et al., 2013). Analysis of the radar traces recorded for site 33 may be suggestive of beaver created structures. A mineral layer can be observed from point 7 to just before point 17 (see Appendix C). This layer gradually thickens and then is abruptly interrupted, with the trace then showing evidence of a mineral layer re-establishing approximately 8 m further south. This could possibly represent the mineral base of a beaver pond, getting gradually thicker as it gets nearer to a dam, and then stopping at the location of a dam. This is speculative, as the same feature may be explained by any number of processes, for example, an old stream channel cutting across the mineral material. However, beaver currently inhabit this wetland, and all historical air photos show beaver ponds, meaning beaver are a strong candidate to have left a signature in the sub-surface. Overall, it is likely that the interbedding of different materials in the studied peatlands represents a combination of environmental and bioengineering impacts. Given the high percentage of peatlands in the study area that show impact by beaver, and that there is evidence of beaver having evolved in step with peatlands since the deglaciation of North America (Johnston, 2001; Gorham et al., 2007), further research into the influence of beaver on the subsurface structure of peatlands is warranted.

Peatlands are hydrologically and biogeochemically complex (Roulet, 1990; Mitchell and Niering, 1993; Racine and Walters, 1994; Bragg, 2001; Holden, 2008), in part due to subsurface heterogeneity. Internal peatland structure influences the rate at which water flows through a peatland (Holden, 2008), with the upper layers of peat (acrotelm) being more permeable, and the lower layers (catotelm) being relatively impermeable (Reeve et al., 2000). The dynamics of water movement through a peatland in turn influences biogeochemical processes such as carbon sequestration (Roulet, 1990; Bragg, 2001). The soil coring and radar imaging results show that mountain peatlands have a much more complex subsurface environment than those typically studied. One of the few studies on mountain peatland stratigraphy (Engel et al., 2010) describes a peatland in the Czech Republic that has a thin layer of peat at the surface, underlain by mineral material, then undecomposed peat, another mineral layer, then a layer of decomposed peat, and then underlain by several layers of varying mineral material. How layering affects the hydraulic properties of peatlands, groundwater flow through peatlands and C sequestration capacity is not yet clearly described in the literature.

5. CONCLUSIONS

The purpose of this thesis was to improve our understanding of Canadian Rocky Mountain peatland abundance, as affected by beaver, and to investigate the subsurface structure of these peatlands. This was done through meeting four study objectives.

For objective one, the distribution of beaver impacted wetlands, a GIS analysis was carried out. Distribution has been assessed in terms of physiographic setting, and sociological factors. The majority of wetlands in the study area are found in the foothills region (396 out of 529). Nearly all of these are located in the Municipal Districts area, which contains 361 out of 529. Evidence of beaver impact was found in 30% of the 529 wetlands. These beaver impacted wetlands are unevenly distributed across the physiographic and jurisdictional range of the study area. Physiographicly, beaver impacted wetlands appear to be limited by the availability of habitat; restricted to valley floors, and areas of low gradient. When analysed by jurisdictional location, it was found that beaver impact was least apparent in the Municipal Districts, with 20% of wetlands showing evidence. In the First Nations Reserve, 40% of wetlands showed signs of impact. Improvement Districts and Alberta Parks showed similar proportions of beaver impacted wetlands at 60% and 59%, respectively.

The second objective aimed to find out what proportion of beaver impacted wetlands are peatlands. To achieve this, a subset of the wetlands were ground-truthed to quantify the proportion of those that were peatlands. In total, 15% of wetlands identified in the study area were sampled to determine soil type. Peat or peat-forming soils were found at 77% of the ground-truthed wetlands. Three quarters of wetlands ground-truthed were chosen specifically because they have evidence of beaver impact. Of these beaver impacted sites, 75% were found to have peat soils. The Foothills region has proportionally more beaver impacted wetlands that have peat or peat-forming soils than the Mountain region; 82% compared to 68%. In the Jurisdictional areas, the Municipal Districts and Improvement Districts had similar proportions of beaver impacted wetlands having peat soils with 77% and 76%, respectively. Alberta Parks had a lower proportion at 71%. Unfortunately no data were available for First Nations Reserve wetlands as land access could not be negotiated.

For objective 3, a manual analysis of pond area using aerial images was carried out to determine beaver impact on surface water area. Beaver activity was clearly shown to increase the area of surface water on wetlands in the study area. Despite the potential for subjective error in the actual surface water area as a result of the methods used, the results show that sites with beaver impact, on average, have an open water area an order of magnitude higher than those without. Given the proportion of wetlands impacted by beaver, and the proportions of those that are peatlands, it follows that surface hydrology of peatlands in the study area is being influenced by beaver.

For objective 4, the goal was to describe the subsurface stratigraphy of beaver impacted peatlands. Ground penetrating radar surveys and soil-coring were carried out at nine wetlands that had been previously ground-truthed. Of these nine sites, eight showed at least some subsurface layering of mineral and peat material. Several of the peatlands surveyed showed extensive layers of mineral material interbedded in the peat matrix. Site 33 and 903 were surveyed in greater detail. It was possible to show the partial extent of one mineral ‘lens’ within the peat for site 33. This lens extended north to south for approximately 80 m and east to west for over 30 m in places. Site 903 also showed an extensive mineral layer extending east to west for at least 60 m. The GPR surveys were generally useful for identifying at least one layer of mineral intrusion. Although these surveys were limited by the depth of signal penetration and resolution limitations of the equipment configuration, soil core data recorded on site supported the notion of subsurface complexity. A number of cores showed mixtures of mineral material within the peat, and gradual changes in the peat/mineral ratio.

This research has identified significant gaps in knowledge with respect to the location and functioning of wetlands and peatlands in a mountain and foothill setting. An inventory such as this one is a necessary first step to base further research into their development, function and importance on the landscape. Inventorying of landscape units is also necessary to aid their management and monitoring. This work complements the Canadian inventory work being led by Ducks Unlimited Canada (Fournier et al., 2007) and the provincial peatland inventories provided by Vitt et al. (1996) and Halsey et al. (1997) as I provide details on the distribution on individual peatlands that would be difficult to include on a larger scale inventory. Details such as physiographic location, jurisdictional area, specific location, soil type and biotic influences, are necessary for successful local management strategies. Although there are limitations related to the inventory, it was clearly demonstrated that peatlands are a major component of this region's wetlands. Further study is warranted to provide more up to date data (for example, using LiDAR) using the most modern remote sensing techniques available.

The inventory provided herein showed beaver are impacting the hydrology of peatlands in the study area, as demonstrated by examining one hydrological variable, water storage. Other influencing factors on beaver distribution, although not studied, are likely to be land and wildlife management practices. Jurisdictional differences in beaver impact on wetlands suggest that human/wildlife interaction has an influence on beaver colonisation patterns which in turn influences surface water area, and hydrological and biogeochemical processes. There are distinct differences in beaver impact on wetlands between the jurisdictions, which is likely at least partially the result of different land management practices and developmental priorities. Other possible influences include the availability of food and density of predators, both of which may also be influenced by land management practices. Beaver activity has been shown to influence surface water area, with beaver impacted wetlands on average having ten times greater surface water area. Changes in surface water area will have implications with regards to hydrology, biogeochemistry and vegetation succession. Therefore, by extension, the beaver population will also influence these factors on a regional scale. Much is already known about how beaver impact the function of alluvial systems, as described by the Beaver Meadow Formation Theory (BMF; Ives, 1942; Terwilliger and Pastor, 1999). However, the BMF currently does not include how beaver influence peatlands. Therefore more study is required to understand these particular processes, and develop a wetland analogue or addition to the BMF theory.

The complexity of these peatlands is a further indication that more research is required to understand their function. The prevailing knowledge of peatland function is based on stratigraphically homogeneous sites. However, the sub-surface investigation carried out herein has shown mountain peatlands to be complex. Therefore, what is already known about peatland hydrology, biogeochemistry and vegetation does not necessarily apply. Research needs to be carried out to determine both, the environmental conditions that led to this complex stratigraphy, and the impact of this complexity on hydrological and biogeochemical functioning.

As well as a lack of scientific knowledge relating to the function of mountain peatlands and the role beaver play, there are no official beaver management policies in the region. The province of Alberta has an annual pelt harvest limit which applies in all but a few protected areas. What can be seen from jurisdictional differences in beaver impacted wetlands is that different practices are being applied on the ground. It is likely that the most widely beneficial management policies would result from understanding they have historically responded to climatic and environmental change, and how human activity has influenced their development in more recent times. By being able to understand something about how these wetlands may have functioned before human influence, it may be possible to determine scenarios resulting from different land management practices, which could be used to inform planning decisions. This study shows that differing land management practices in the four jurisdictions likely have an influence on the hydrological function of wetlands.

This research suggests that human activity may be influencing beaver distribution in the study area. However, there are likely to be other contributing factors which have not been investigated here. Food availability and predation are also likely to influence colonisation by beaver, although these are also likely to be affected by human activities such as logging, ranching and tourism. Beaver are influencing the surface hydrology of mountain peatlands. These peatlands have also been shown to be structurally complex and unlikely to fit with existing hydrological models. Peatlands in the Rocky Mountains are located near headwater streams that feed the Prairie Provinces and are therefore critically important resources. Combining this with their proven sensitivity to environmental changes, it is clear that further scientific research is needed to better understand this resource and develop relevant management policies to protect it.

APPENDIX A – Wetland database excerpt

Site ID	UTM_X	UTM_Y	Visited?	Peaty?	Beaver?	GPR?	Wetland area (km2)	No. of ponds	Open water Area (m2)	Geog div	Jurisd div	Elevation	EC	Water Temp	Date	Distance to nearest road* (m)
1	656671	5592036					0.012	0	0	M	AP	1757				1113.32
2	673194	5603863					0.036	0	0	F	ID	1586				519.03
3	632758	5614761					0.085	0	0	M	AP	1719				88.25
4	633051	5613248	Y	Y	Y	Y	0.458	3	218	M	AP	1689	312	14.1	20th June 2012	0.00
5	633585	5616286					0.017	1	27	M	AP	1630				383.60
6	627525	5609956					0.221	0	0	M	AP	1730				3636.47
7	627063	5610732					0.128	0	0	M	AP	1732				4201.28
8	632819	5619256	Y	Y	Y		0.125	12	4647	M	AP	1613	872	12.5	14th June 2012	0.00
9	633311	5617187	Y				0.110	13	8334	M	AP	1631	7.8	17	20th June 2012	41.94
10	631897	5617796					0.083	2	3848	M	AP	1674				0.00
11	632386	5618516					0.015	0	0	M	AP	1662				194.05
12	632855	5618708					0.005	0	0	M	AP	1614				175.23
13	633386	5616200					0.074	0	0	M	AP	1672				33.30
14	635372	5611087	Y	Y	Y		0.061	6	3182	M	AP	1795	341	5.2	20th June 2012	868.34
15	634055	5616444			Y		0.055	2	207	M	AP	1660				416.11
16	633930	5617261	Y	Y	Y		0.053	2	496	M	AP	1662	334	17	20th June 2012	279.30
17	634016	5617642					0.052	0	0	M	AP	1660				88.70
18	632498	5618030					0.027	1	2425	M	AP	1657				226.22
19	635448	5610567	Y	Y	Y		0.026	5	834	M	AP	1811	319	9.6	20th June 2012	901.31
20	631969	5620101					0.025	0	0	M	AP	1628				404.85
21	632099	5619261			Y		0.022	0	0	M	AP	1651				168.72
22	635069	5611620	Y	Y	Y		0.020	1	601	M	AP	1765	341	5.4	20th June 2012	943.66
23	617288	5631437			Y		0.332	3	871	M	AP	1838				84.80
24	622670	5648173					0.050	1	1695	M	AP	2194				4367.66
25	616683	5626242	Y		Y		0.501	1	2640	M	AP	1968	255	10.6	19th Jul 12	2648.69
26	659075	5643647					0.038	0	0	M	ID	1517				2290.40
27	658408	5651293					0.028	0	0	F	ID	1504				2306.11
28	648257	5633815					0.022	0	0	M	ID	1837				872.12
29	644843	5643694					0.016	0	0	M	ID	1836				767.33
30	659827	5645254					0.588	0	0	M	ID	1483				1854.80

*From edge of site

APPENDIX B – Aerial imagery metadata

2008 images

Raster Type	TIF/SID
Compression Ratio	0 / 10
Image Resolution (ground)	0.50M
Rotation Angle	0
Mosaic	YES
Scanning Resolution	15 MICRONS
Scanner Model	VX4000HT
Image Source	FILM ROLL
Aerial Photography Scale	1:30 000
Aerial Photography Date	AUG 15,18,& SEPT 4,10,11,13 2008
Aerial Photography Film Type	COLOR
Aerial Photography Roll No.	AS5449,AS5450,AS5451,AS5453
Exposure No. (single exp. only)	N\A
Horizontal Datum	NAD83
Projection	UTM
UTM Zone	ZONE 11
Control Source	APBM\AGPS
AT Methodology	SOFTCOPY
Digital Elevation Source	APBM DEM
Horizontal Accuracy	PLUS\MINUS 3-5METERS
Client:	Contractor:
ASRD	Land Data Technologies Inc
	(780) 451-6477
	ldt@landdatatech.com

2007 images

Metadata for the 2007 images were incomplete. The following information was provided.

Date	2007
Order date	16 Oct 2007
Image type	Colour, 0.5 m resolution
Datum	D_North_American_1983

APPENDIX C – GPR survey data

Site 4 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 4
Scan Samples – 512 Format (bits) - 16 Range (ns) – 150 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 4 Transect layout

Site 4 Transect location overview

Transect order

T1 – 5, 4, 3, 2, 1

T2 – 7, 3, 6

Continuous peat/ mineral layering

Discontinuous peat/ mineral layering

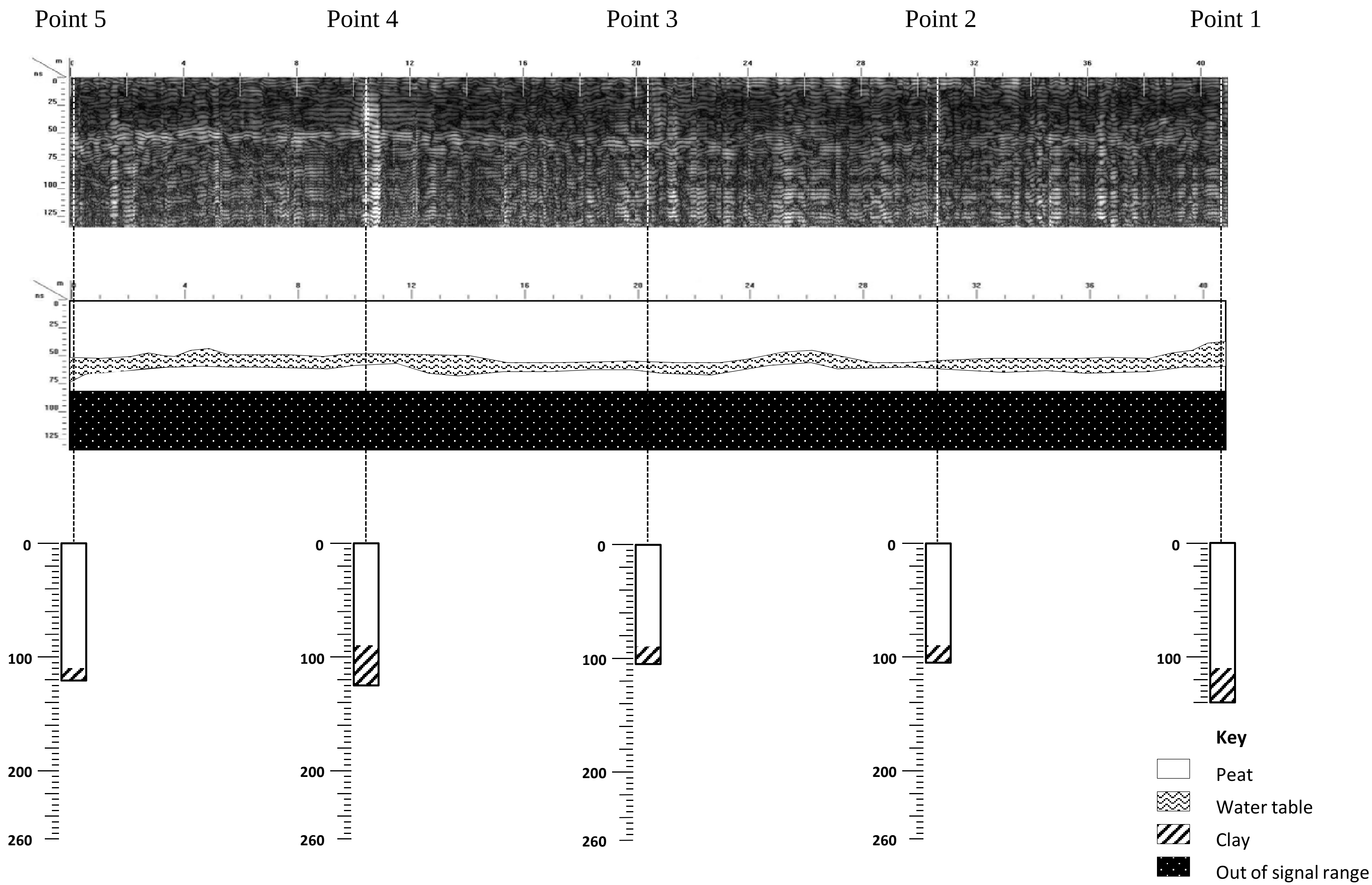
No peat/mineral layering

GPS data

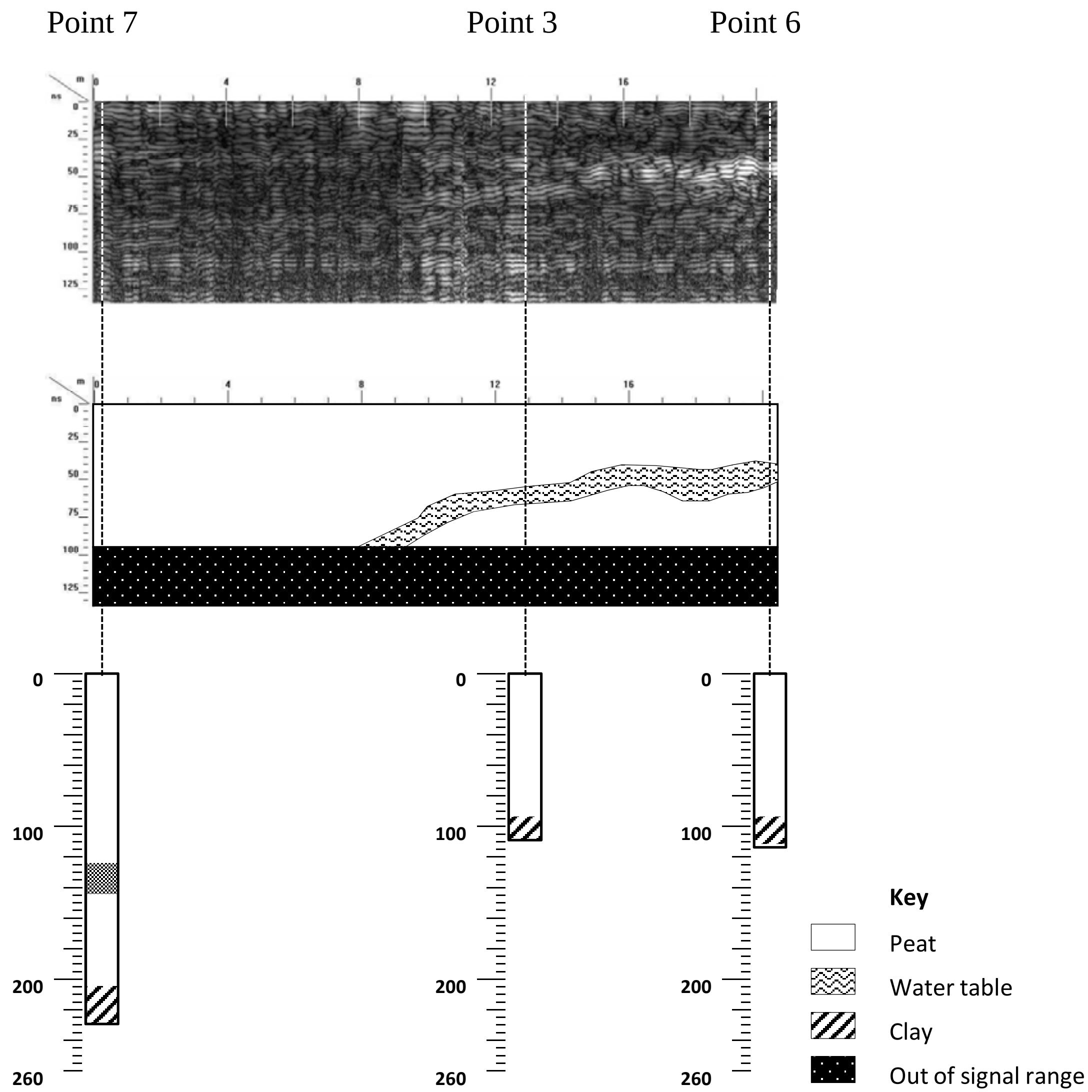
Site 4

	UTM		
Point	**X**	**Y**	**Elevation**
Transect 1			
1	5614023.157	632412.261	1687.623
2	5614014.945	632417.374	1687.337
3	5614007.339	632422.442	1686.512
4	5613996.756	632427.536	1687.11
5	5613990.373	632433.597	1687.307
Transect 2			
6	5614000.643	632417.511	1687.308
3	5614007.339	632422.442	1686.512
7	5614014.868	632431.932	1687.929

Site 4 transect 1



Site 4 transect 2



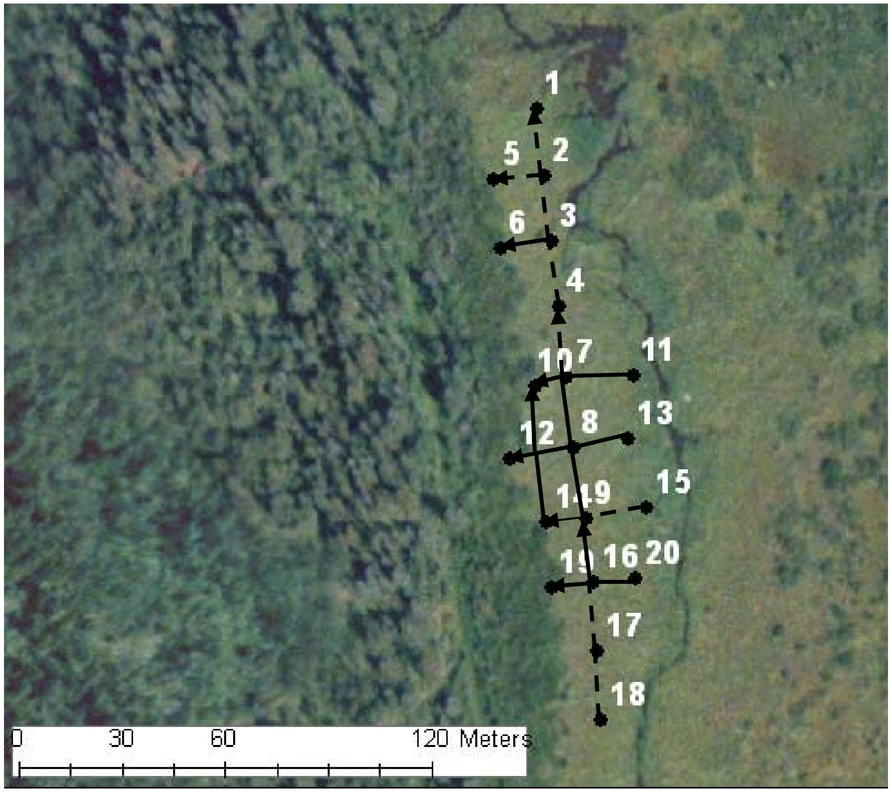
Site 33 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

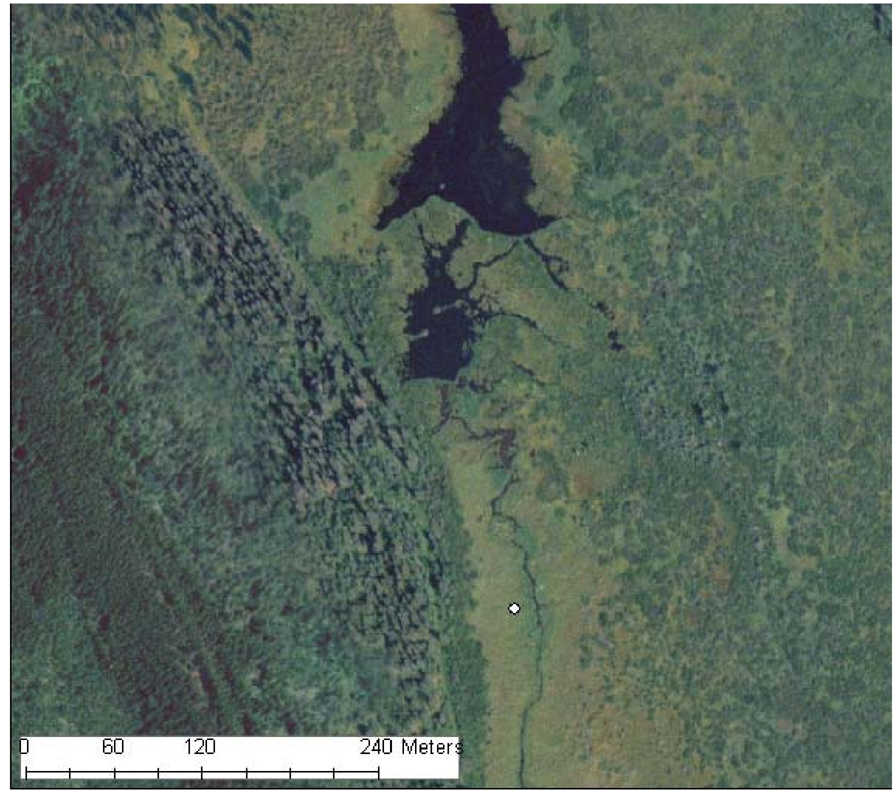
Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 3
Scan Samples – 512 Format (bits) - 16 Range (ns) – 150 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 33 Transect layout



Site 33 Transect location



Transect order	
T1 – 4,3,2,1	T6 – 14,12,10
T2 – 2,5	T7 – 13,8,12
T3 – 3,6	T8 – 15,9,14
T4 – 9,8,7,4	T9 – 18,17,16,9
T5 – 11,7,10	T10 – 20,16,19

——— Continuous peat/ mineral layering

– – – Discontinuous peat/ mineral layering

.... No peat/mineral layering

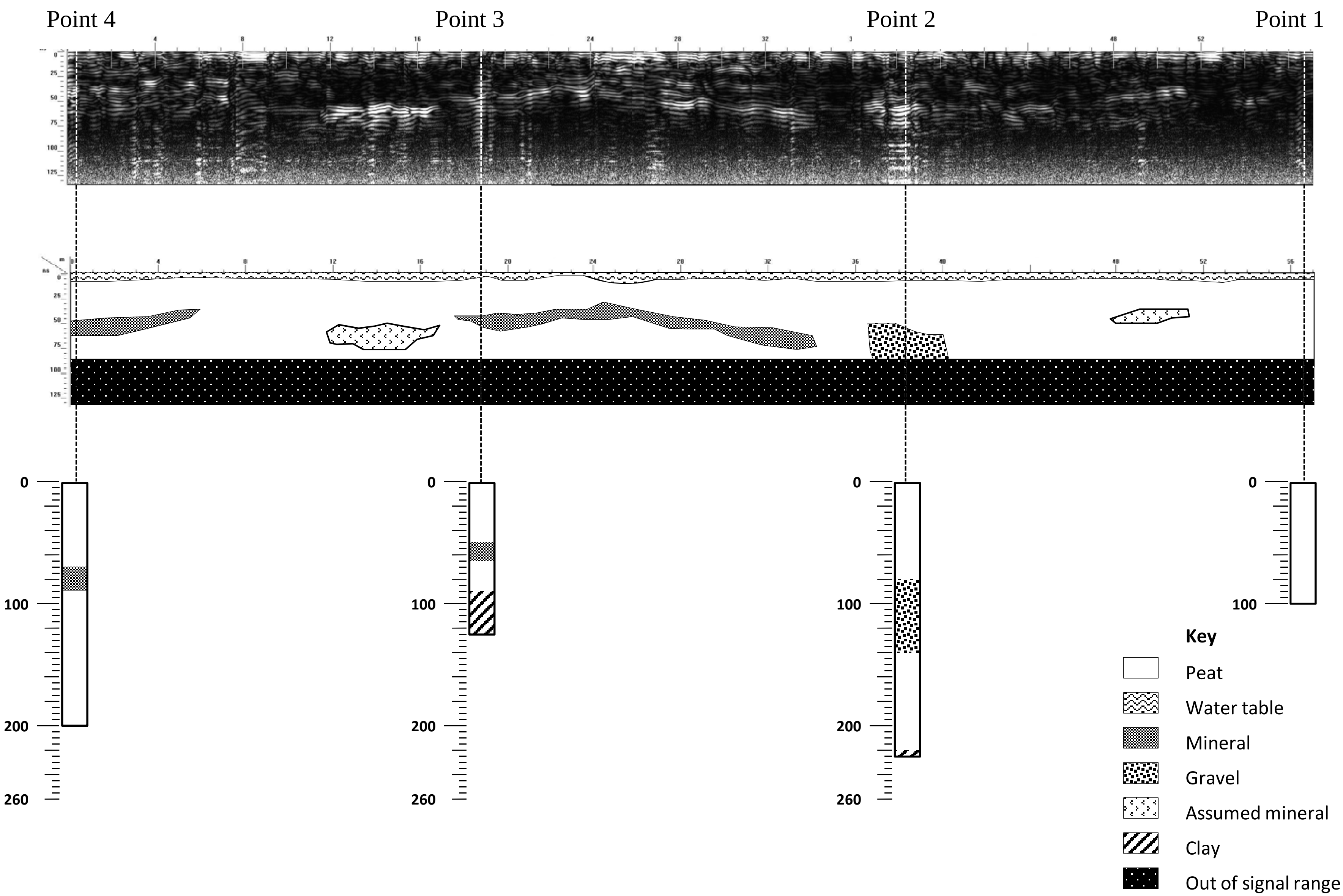
GPS data

Site 33				
		UTM		
	Point	**X**	**Y**	**Elevation (m)**
Transect 1				
	1	649244.75	5658557.53	1498.483
	2	649246.868	5658538.02	1497.766
	3	649249.059	5658518.69	1497.678
	4	649251.272	5658499.65	1498.032
Transect 2				
	5	649232.325	5658536.9	1498.08
	2	649246.868	5658538.02	1497.766
Transect 3				
	6	649234.21	5658516.5	1498.392
	3	649249.059	5658518.69	1497.678
Transect 4				
	4	649251.272	5658499.65	1498.032
	7	649253.466	5658479.2	1496.675
	8	649255.227	5658458.61	1499.849
	9	649258.88	5658437.54	1494.765
Transect 5				
	10	649244.213	5658476.56	1496.311
	7	649253.466	5658479.2	1496.675
	11	649272.728	5658479.74	1495.768

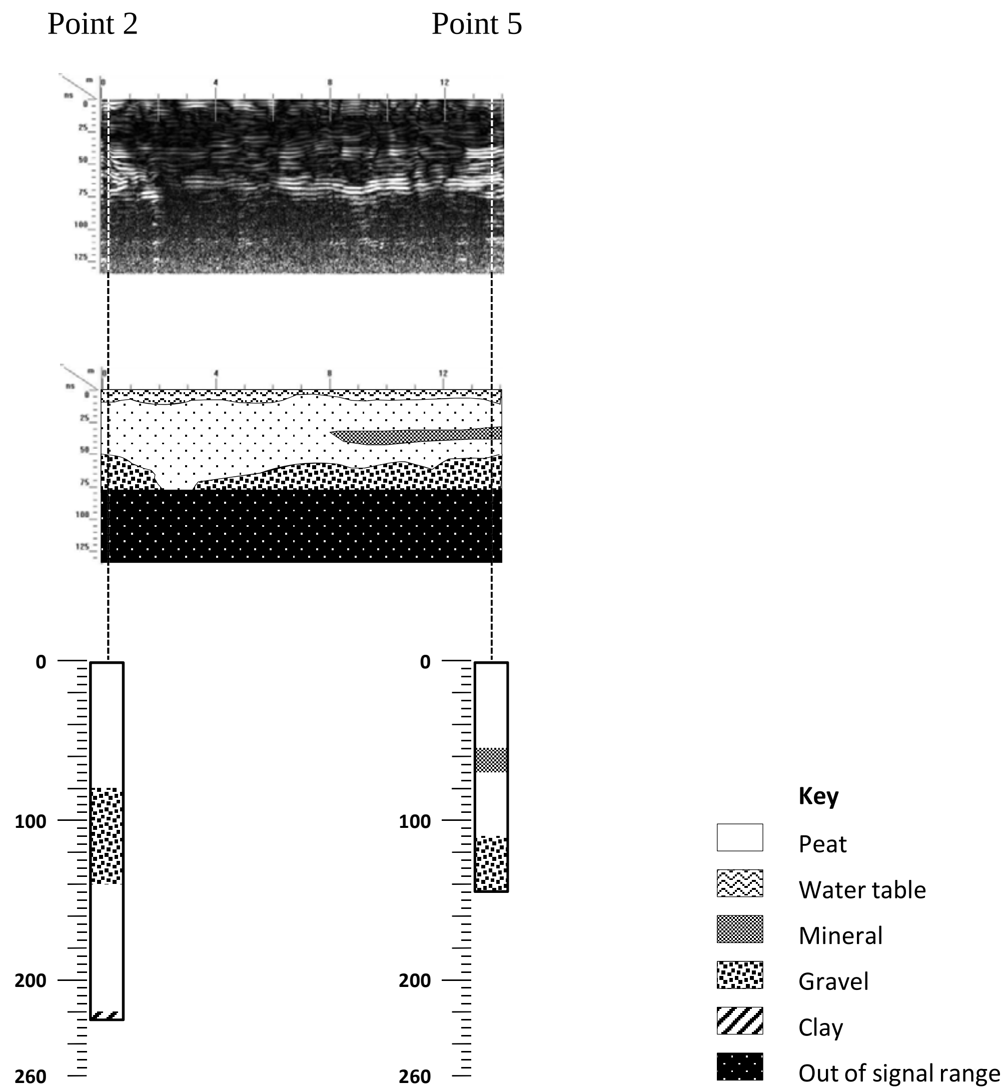
GPS data continued

Site 33				
		UTM		
	Point	**X**	**Y**	**Elevation (m)**
Transect 6				
	10	649244.213	5658476.56	1496.311
	12*	649237.027	5658455.39	1497.437
	14	649247.543	5658436.66	1496.162
Transect 7				
	12	649237.027	5658455.39	1497.437
	8	649255.227	5658458.61	1499.849
	13	649271.309	5658460.99	1497.474
Transect 8				
	14	649247.543	5658436.66	1496.162
	9	649258.88	5658437.54	1494.765
	15	649276.773	5658440.91	1497.268
Transect 9				
	9	649258.88	5658437.54	1494.765
	16	649261.318	5658419.03	1496.769
	17	649262.481	5658398.91	1498.525
	18	649263.399	5658378.8	1497.141
Transect 10				
	19	649248.922	5658417.92	1497.568
	16	649261.318	5658419.03	1496.769
	20	649273.478	5658420.23	1497.227
* Transect passes approximately 2m east of this point				

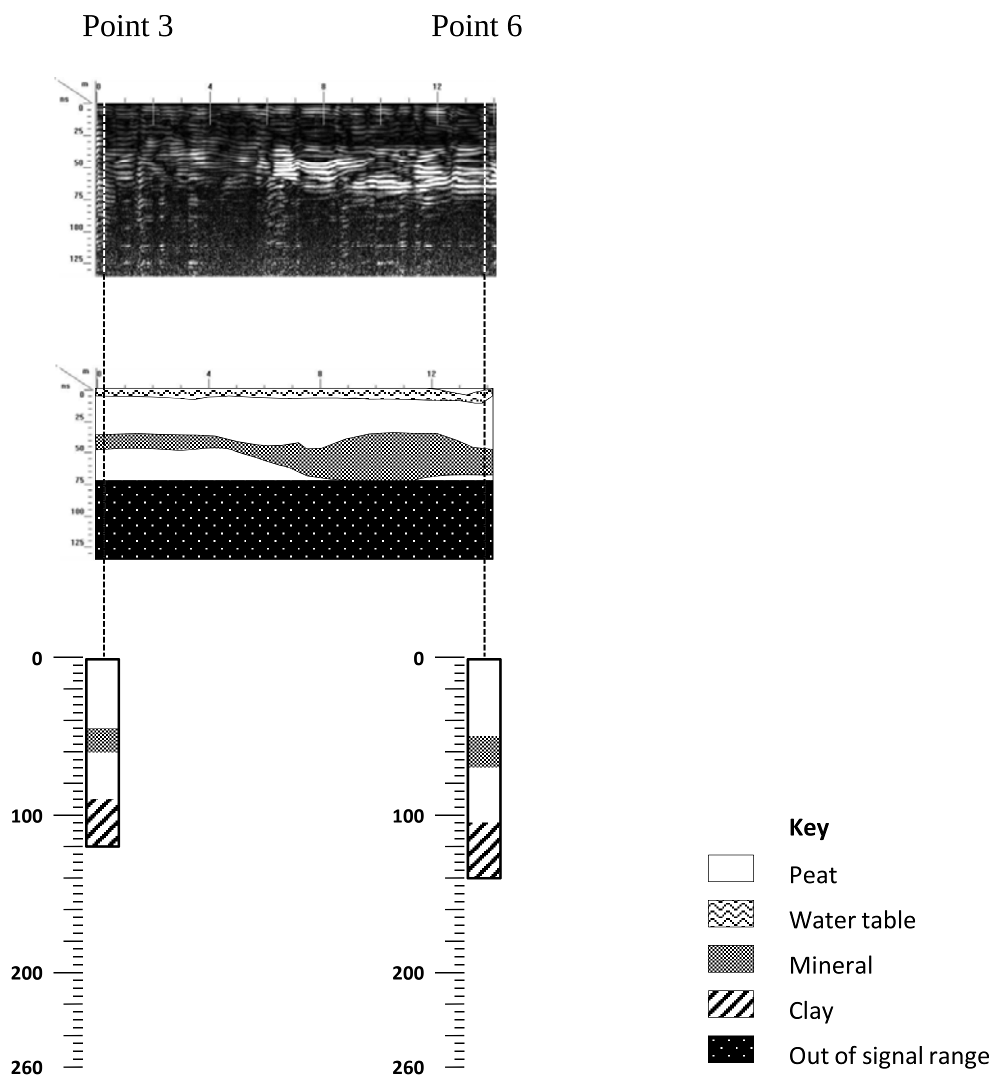
Site 33 transect 1



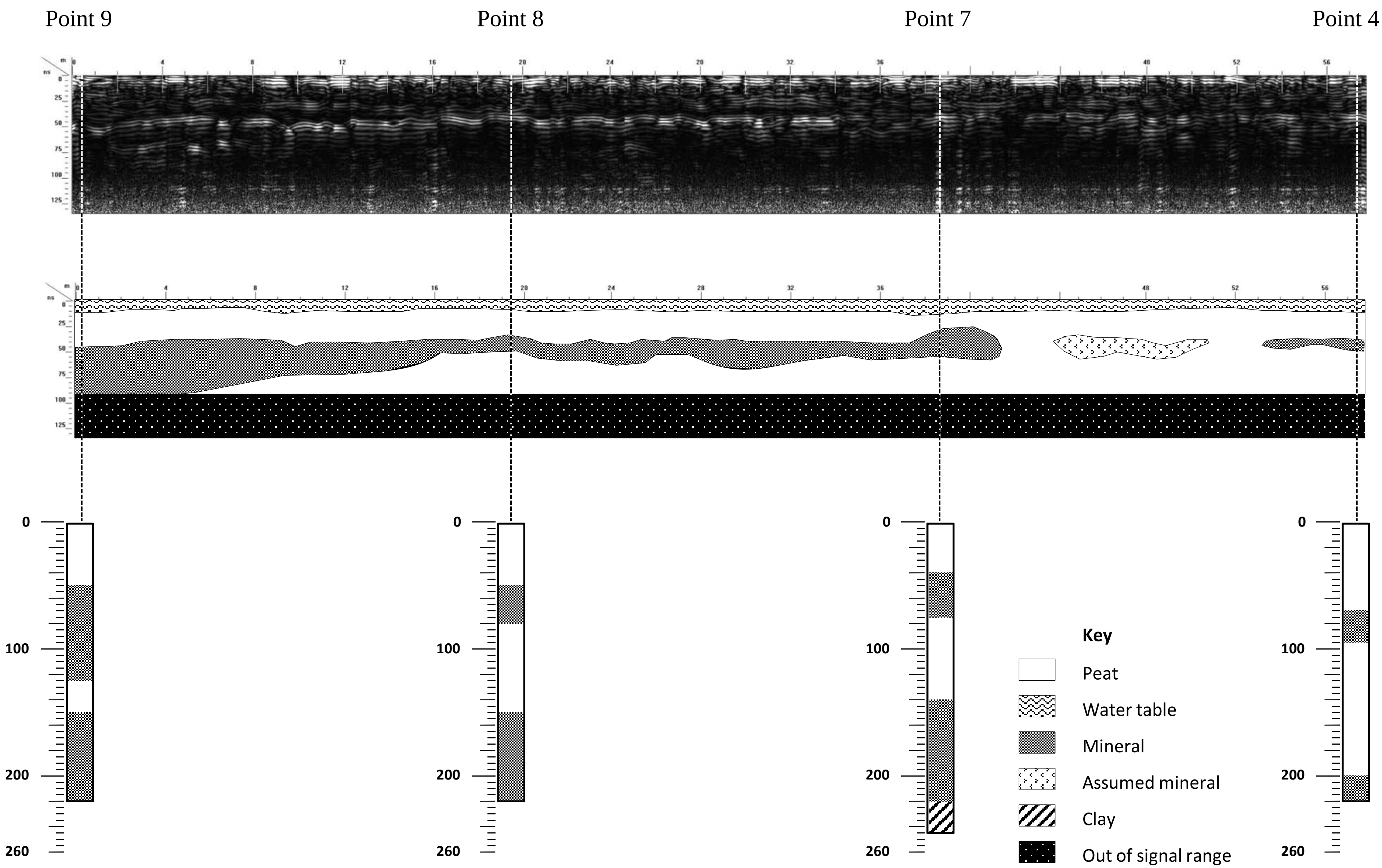
Site 33 transect 2



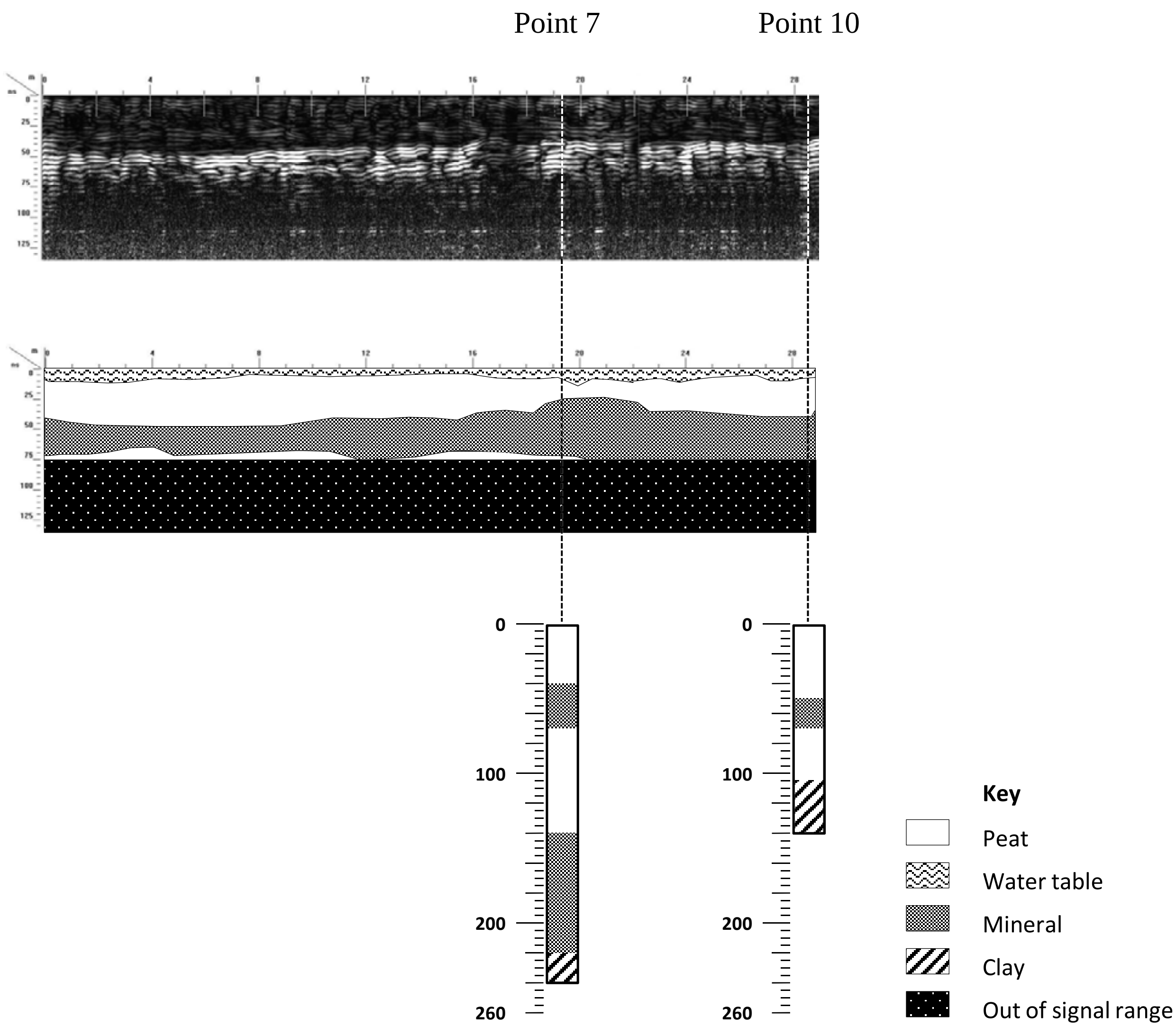
Site 33 transect 3



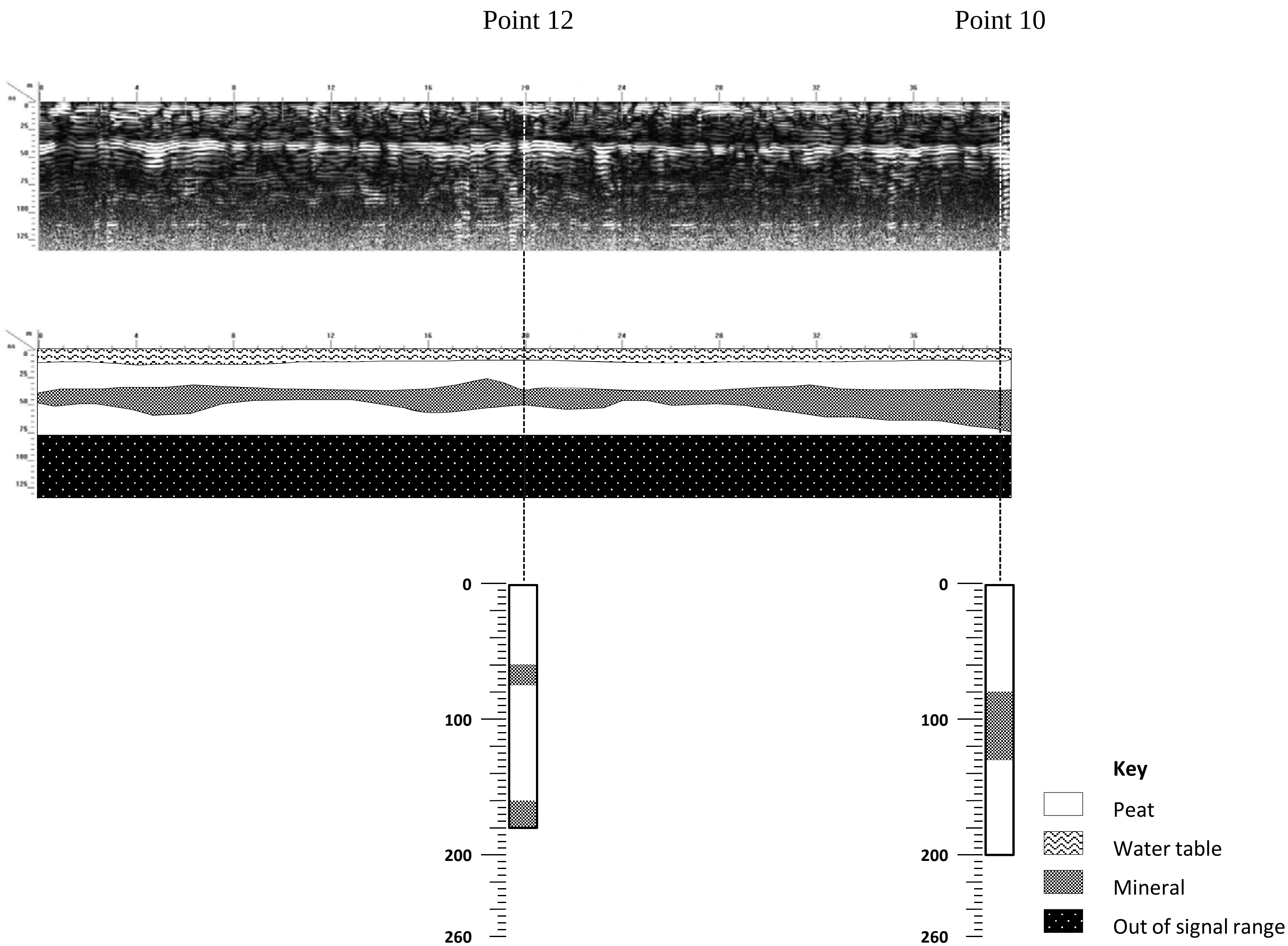
Site 33 transect 4



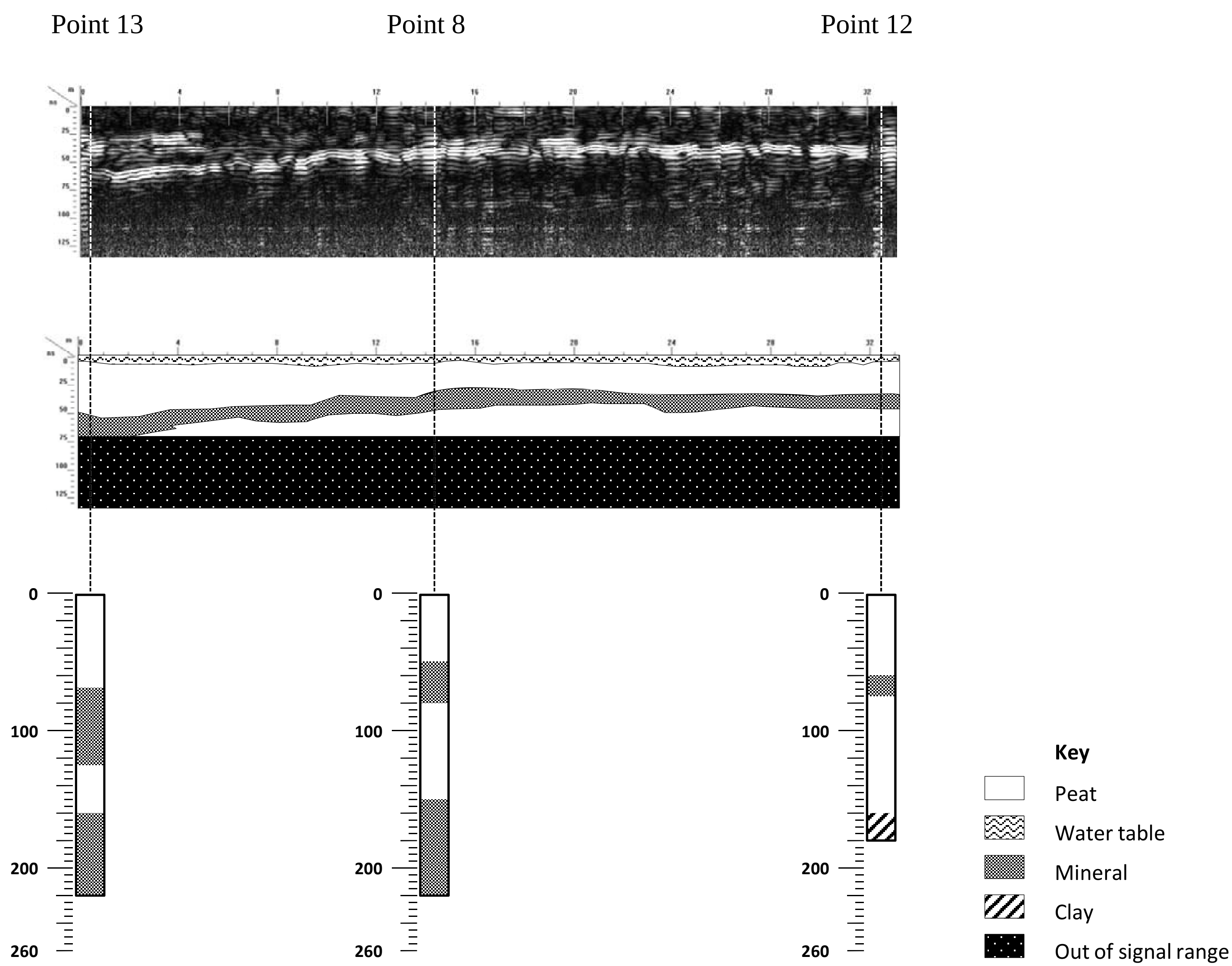
Site 33 transect 5



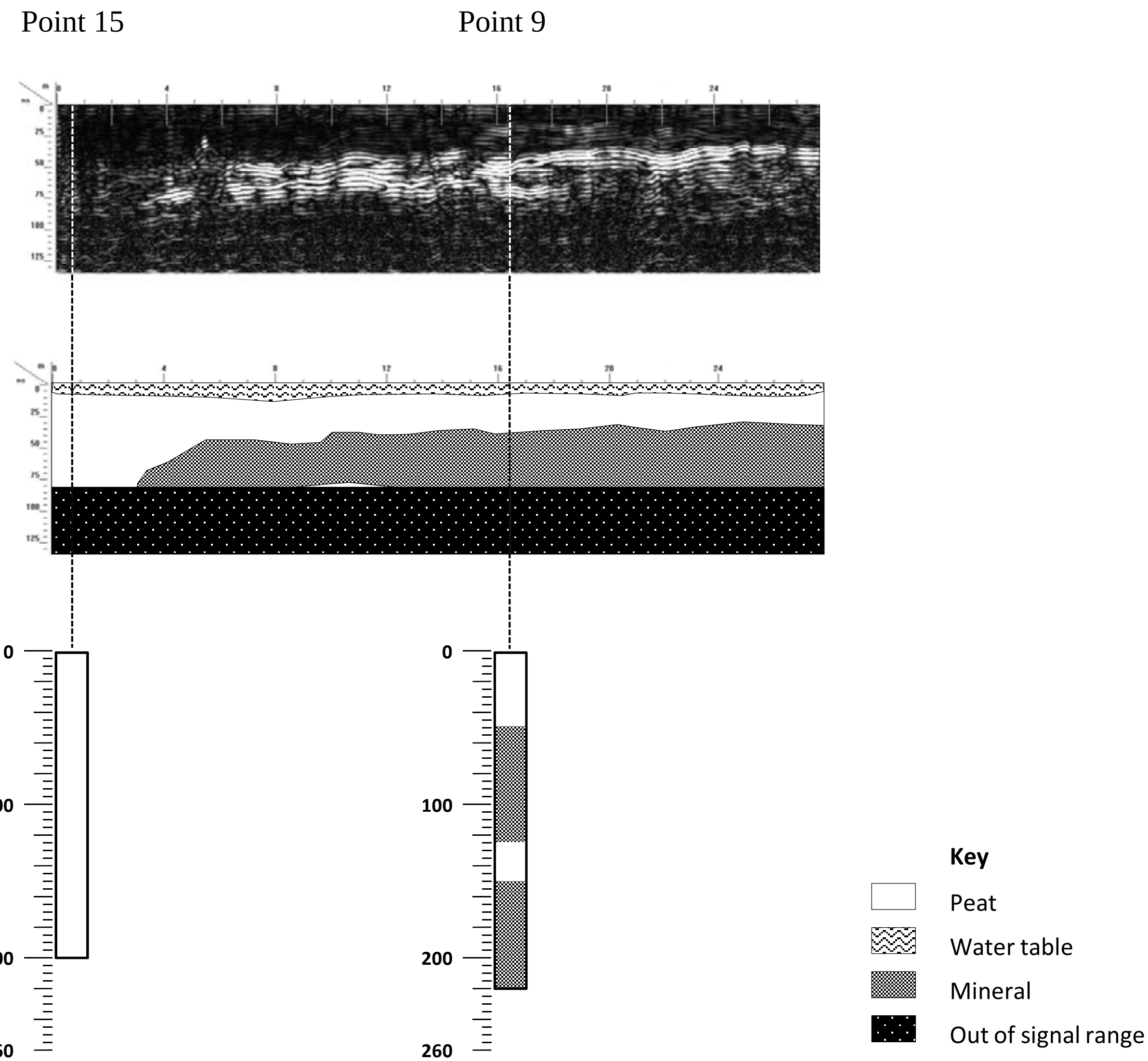
Site 33 transect 6



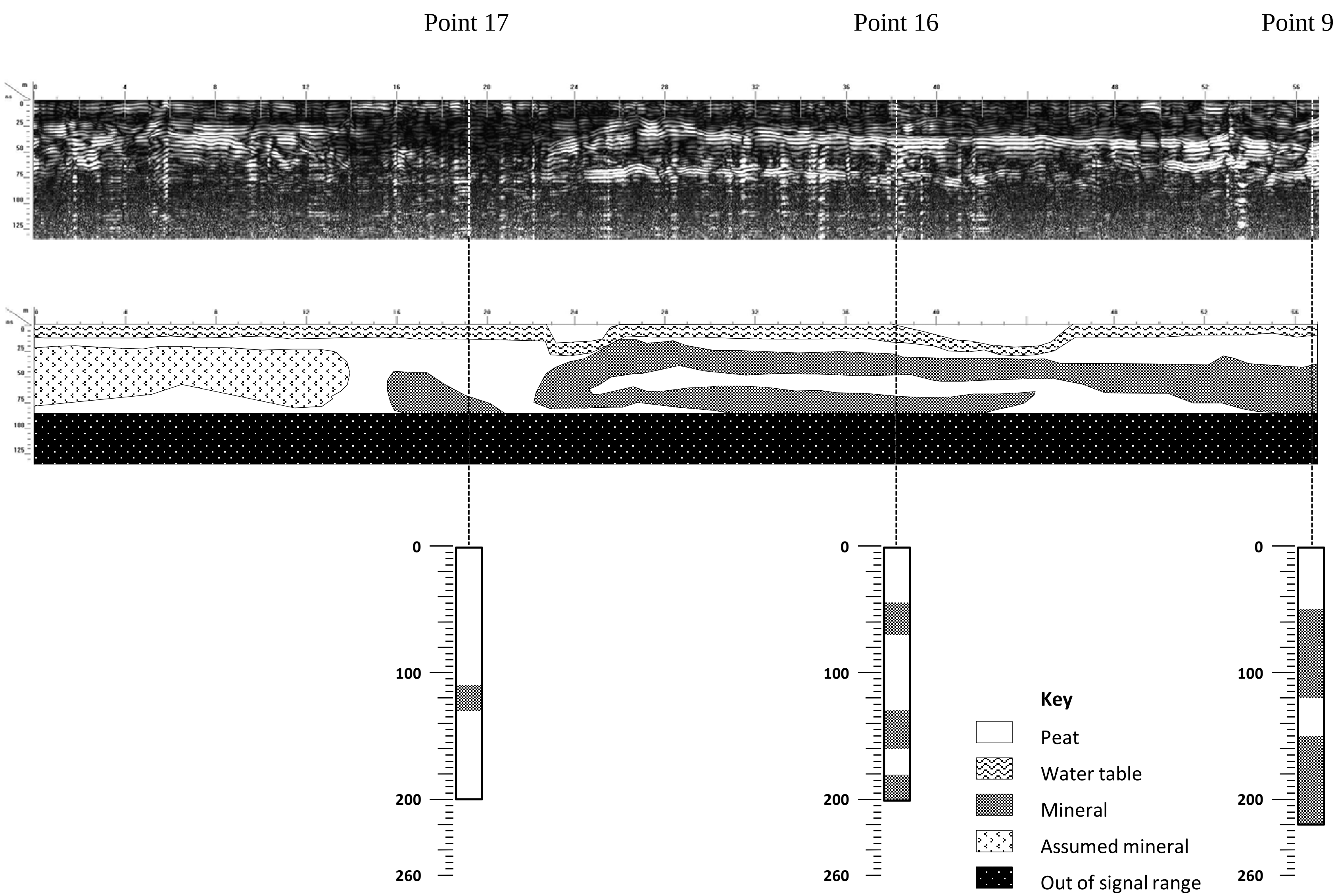
Site 33 transect 7



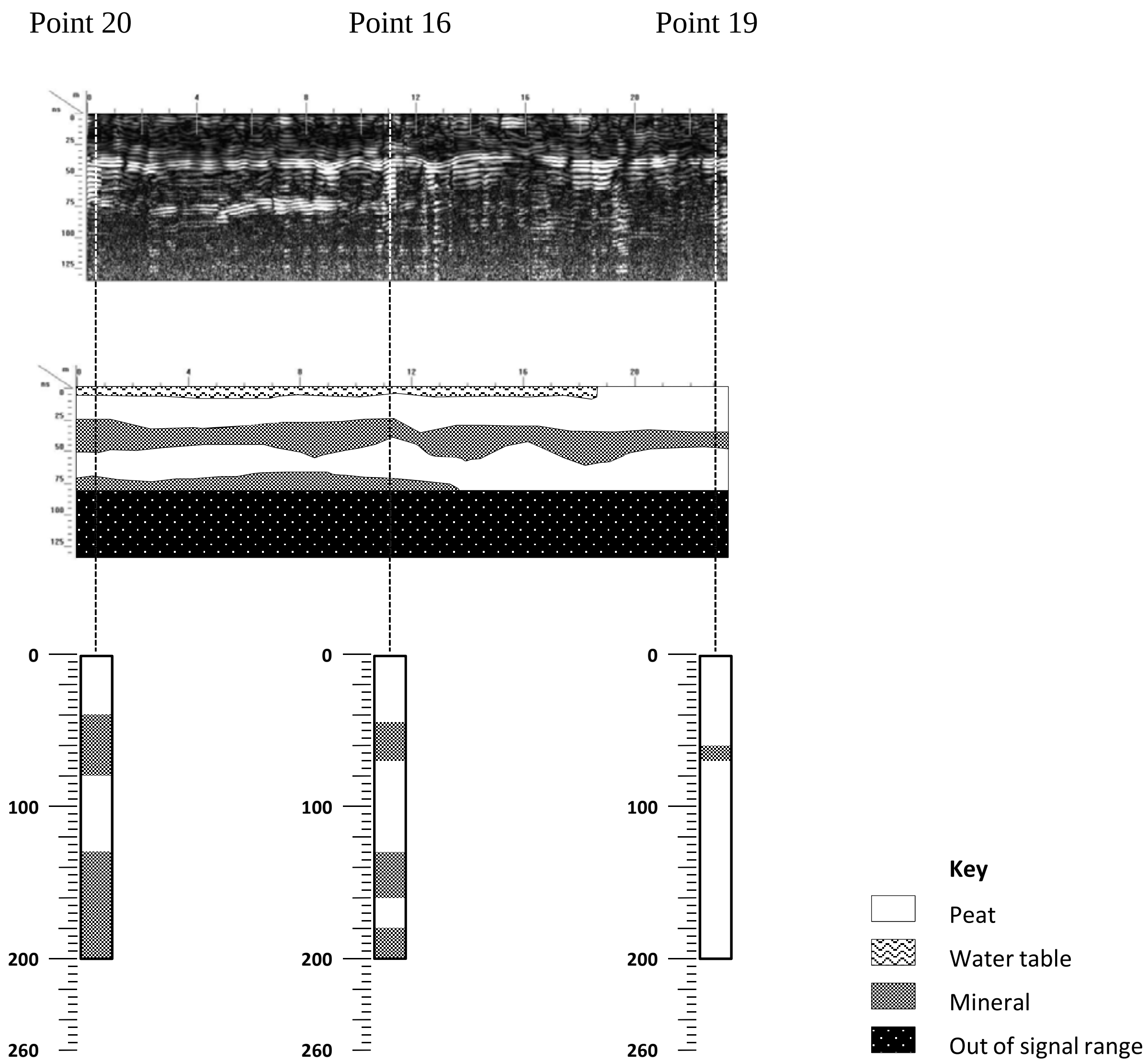
Site 33 transect 8



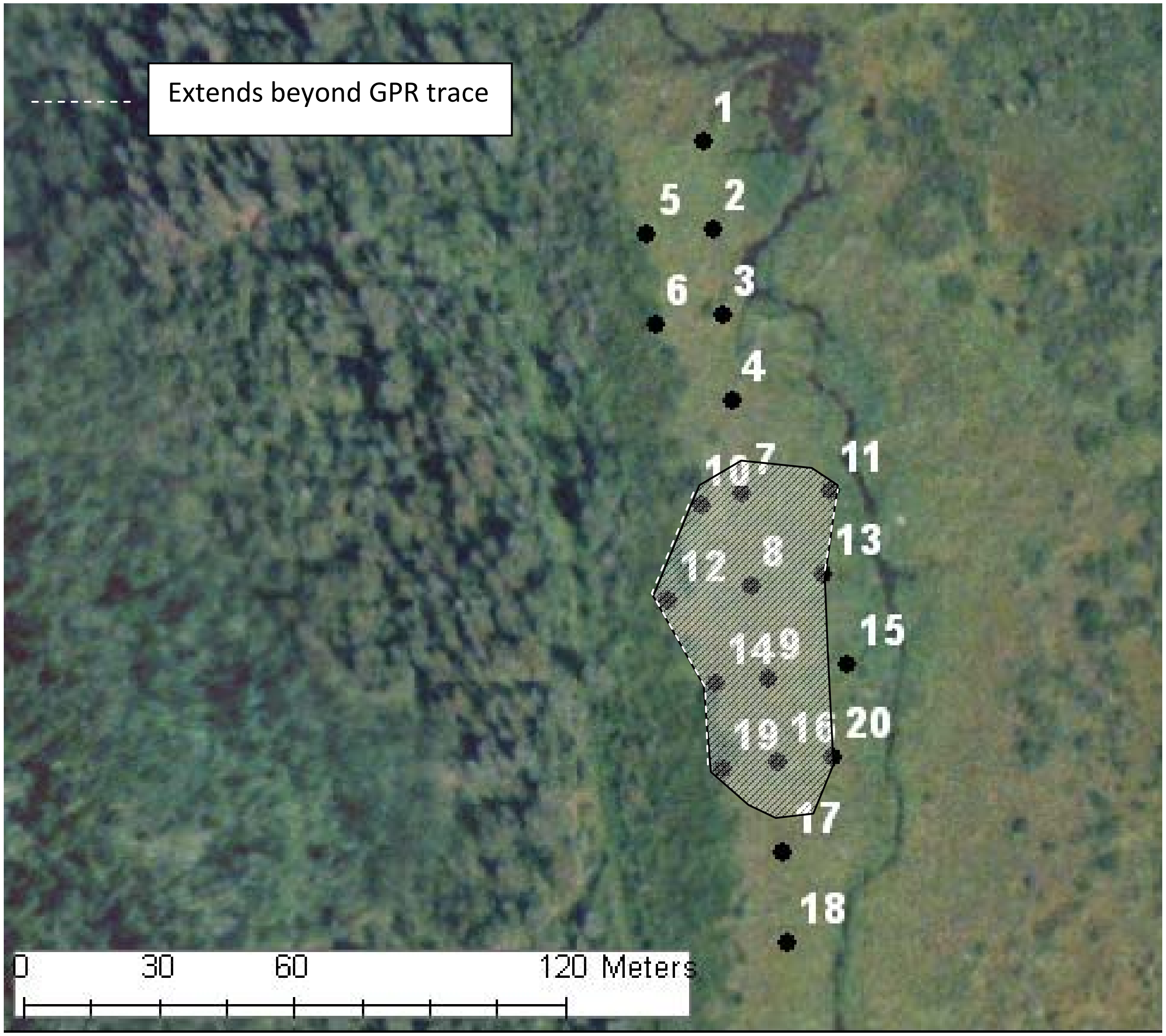
Site 33 transect 9



Site 33 transect 10



Site 33 - Estimated continuous mineral layer extent



100

Site 55 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 5
Scan Samples – 512 Format (bits) - 16 Range (ns) – 150 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 55 GPR transect layout

Site 55 location

Transect order

T1 – 4,3,2,1

T2 – 6,2,5

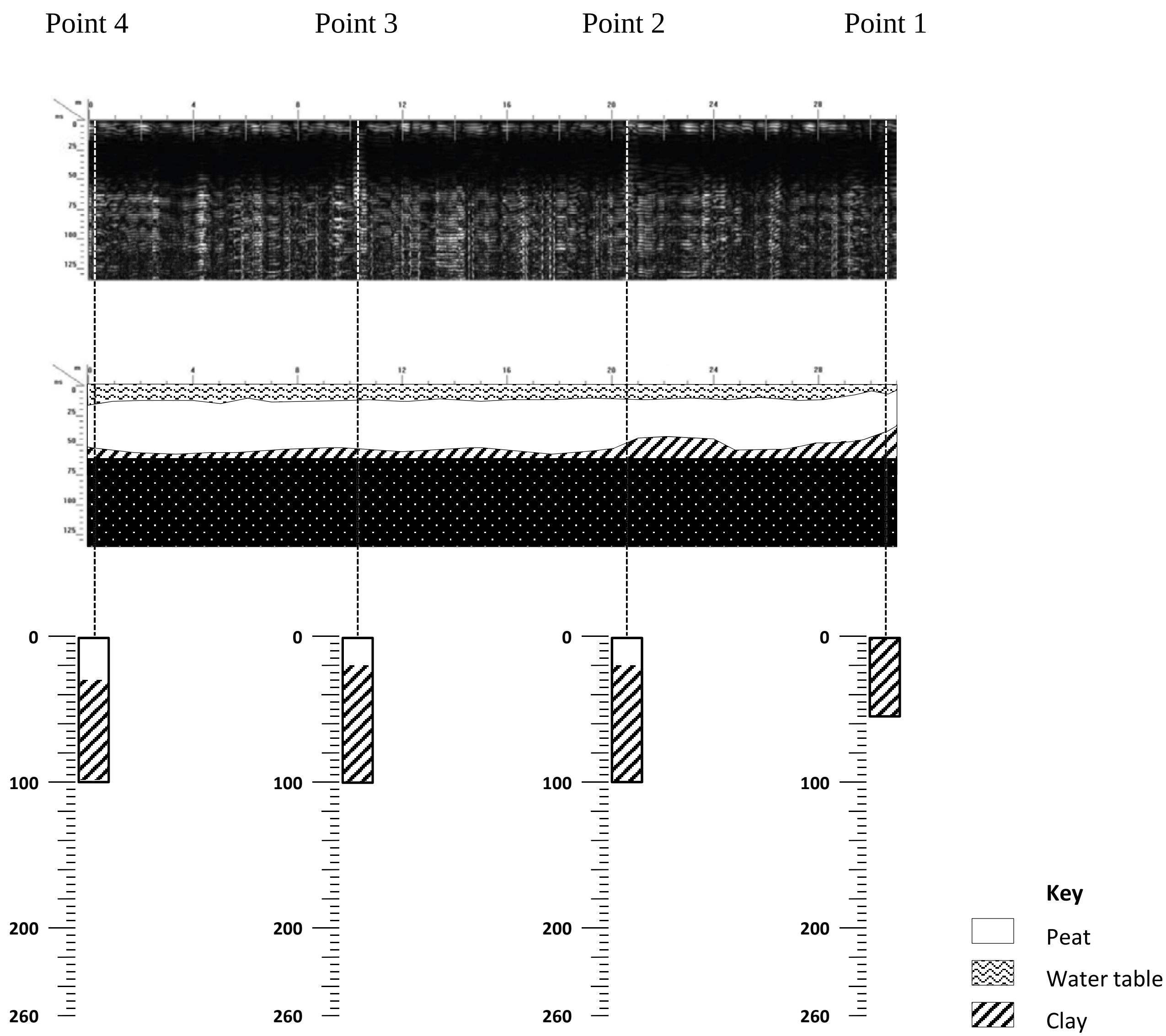
T3 – 8,4,7

——— Continuous peat/mineral layering

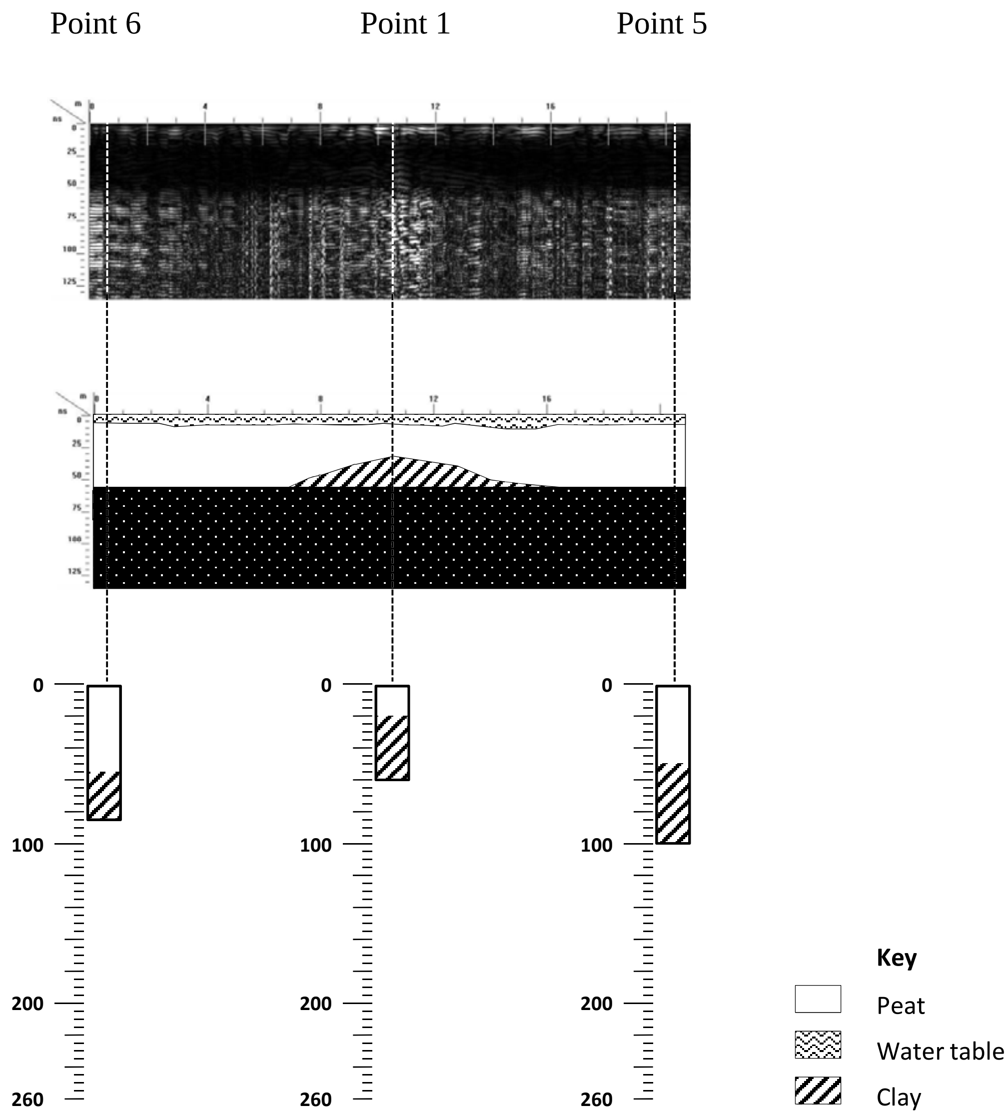
– – – Discontinuous peat/mineral layering

.... No peat/mineral layering

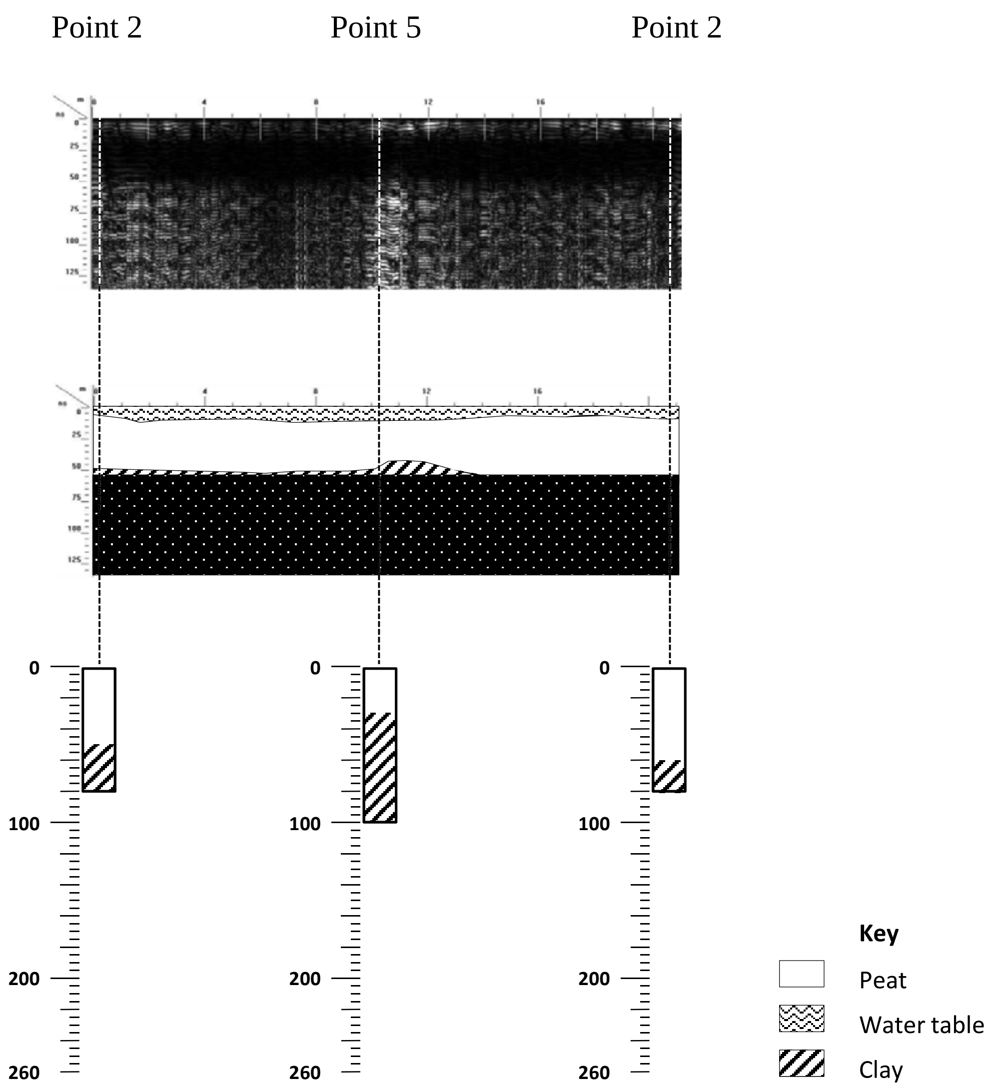
Site 55 transect 1



Site 55 transect 2



Site 55 transect 3



Site 209 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 5
Scan Samples – 512 Format (bits) - 16 Range (ns) – 150 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 209 Transect layout

Site 209 GPR location

Transect order

T1 – 5,4,3,2,1

T2 – 6,2,7

——— Continuous peat/mineral layering

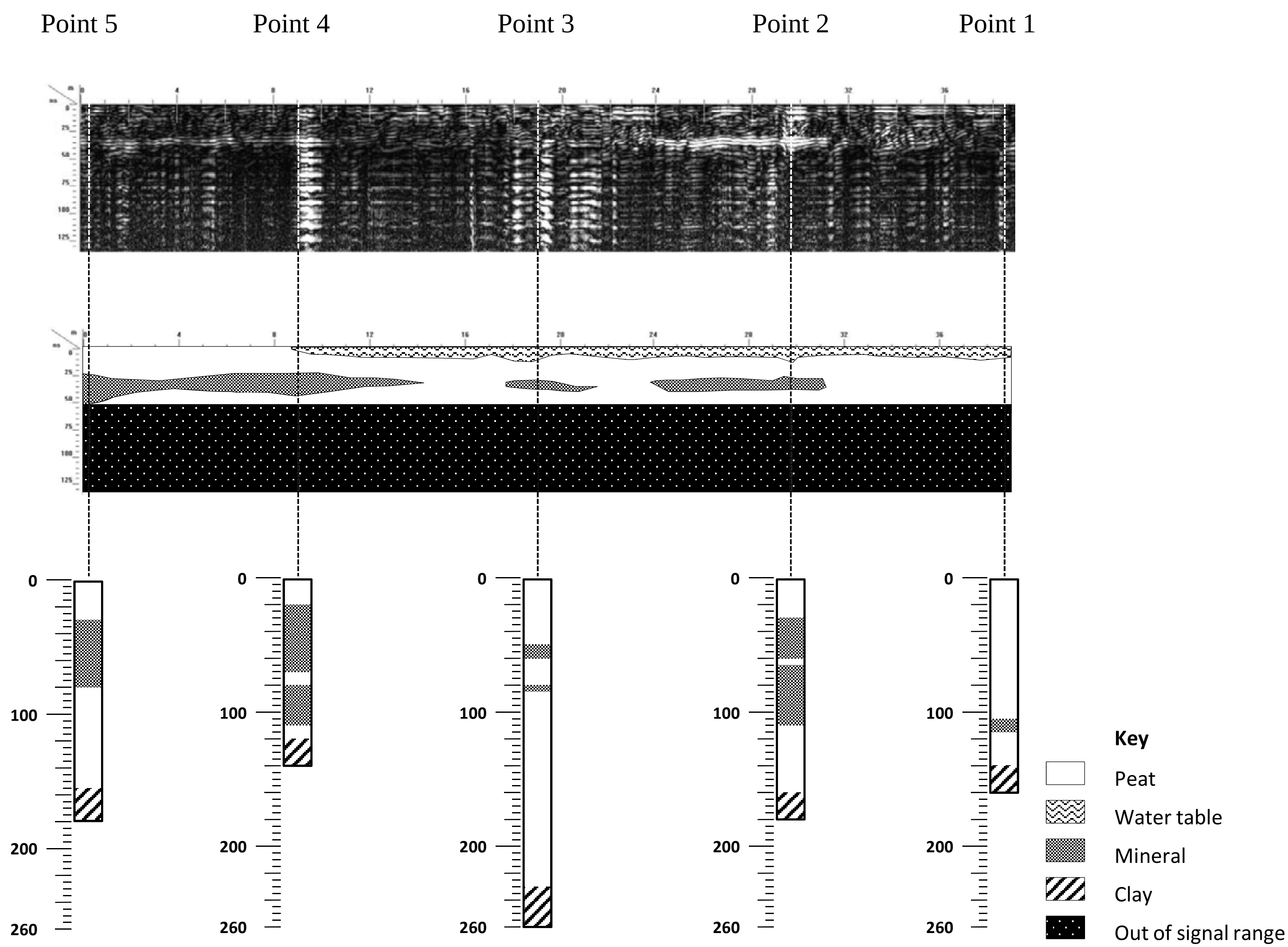
– – – Discontinuous peat/mineral layering

.... No peat/mineral layering

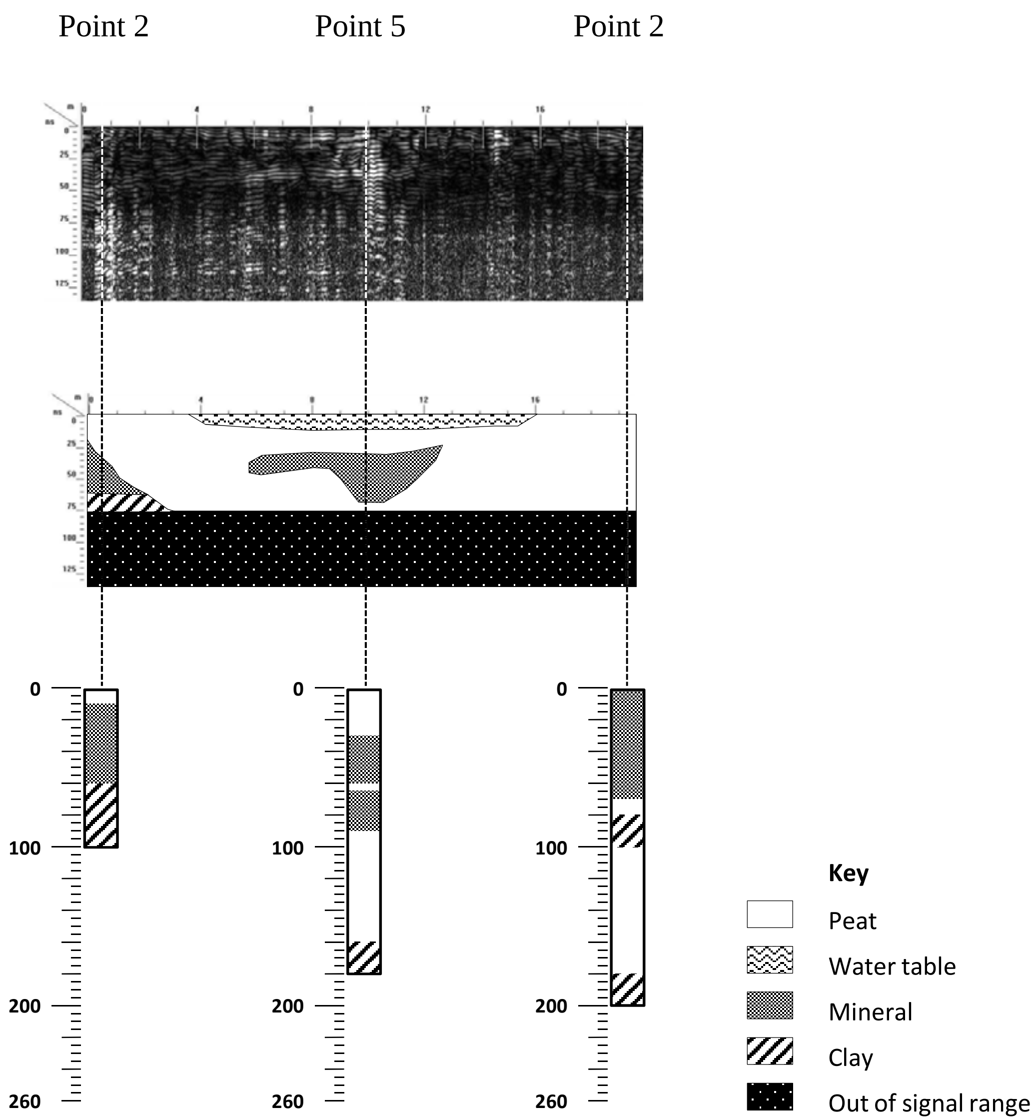
GPS data

Site 209				
		UTM		
	Point	**X**	**Y**	**Elevation**
Transect 1				
	1	5687235.155	641614.073	1460.161
	2	5687230.119	641605.337	1460.25
	3	5687223.552	641597.403	1460.034
	4	5687219.966	641588.879	1459.219
	5	5687214.709	641580.26	1460.031
Transect 2				
	6	5687220.951	641612.07	1460.037
	2	5687230.119	641605.337	1460.25
	7	5687238.198	641601.546	1460.329

Site 209 transect 1



Site 209 transect 2



Site 209 - Estimated extent of continuous mineral layer

Site 490 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 5
Scan Samples – 512 Format (bits) - 16 Range (ns) – 150 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 490 Transect layout	Site 490 GPR location
	

Transect order

T1 – 6,5,4,3,2,1

T2 – 8,3,7

T3 – 9,4,10

T4 – 11,5,12

Continuous peat/ mineral layering

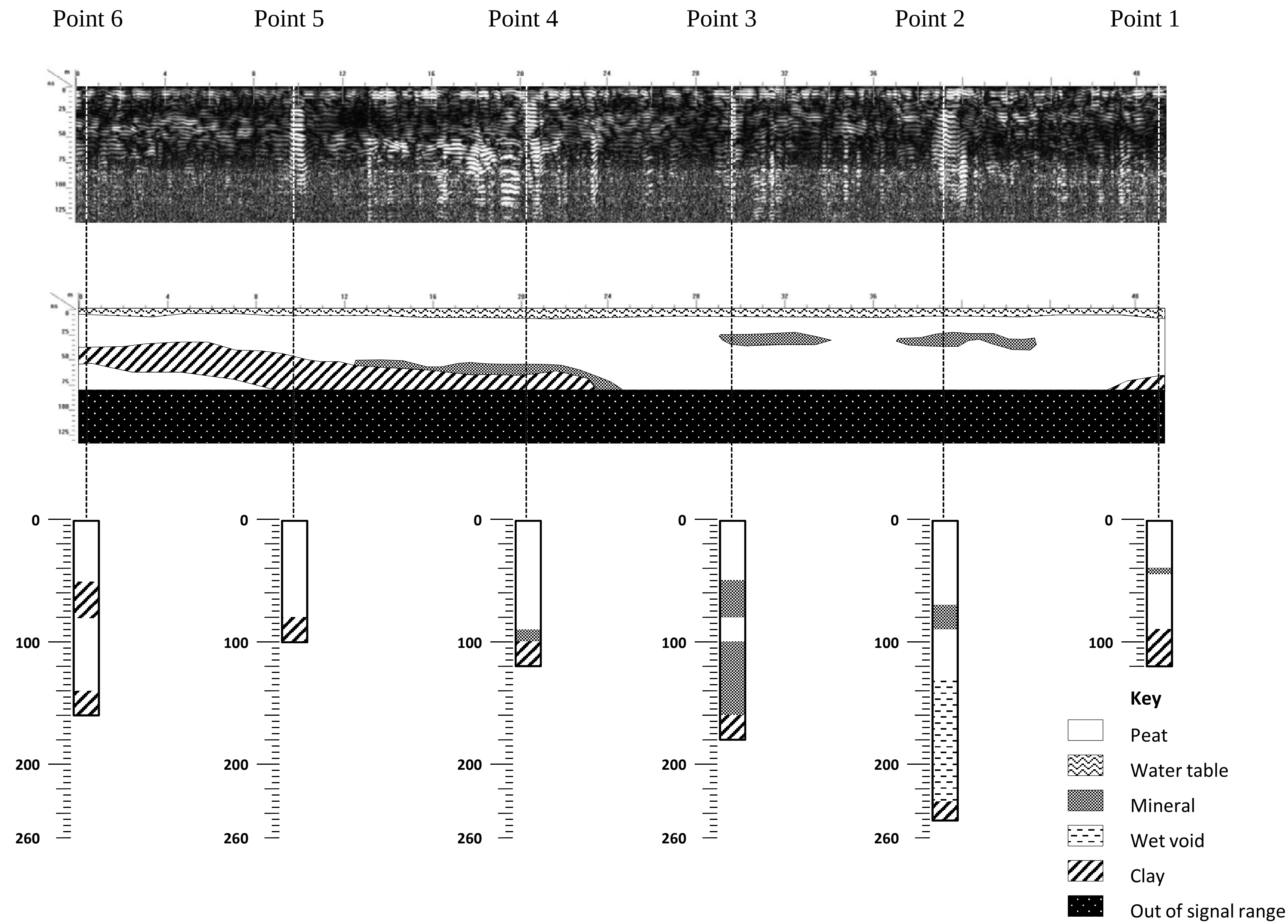
Discontinuous peat/ mineral layering

No peat/mineral layering

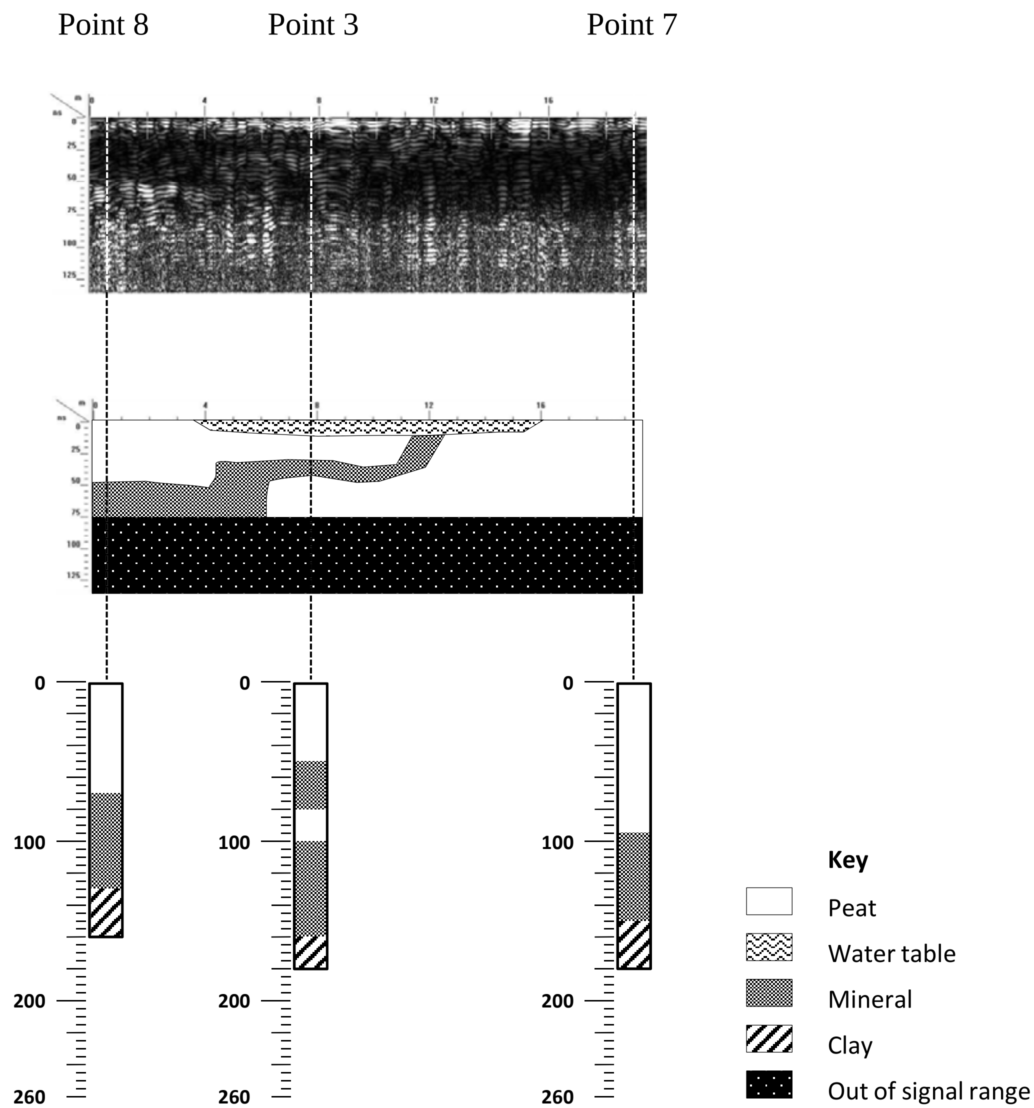
GPS data

Site 490				
		UTM		
	Point	**X**	**Y**	**Elevation**
Transect 1				
	1	617233.158	5738031.678	1476.57
	2	617243.237	5738034.853	1476.82
	3	617252.916	5738038.12	1476.98
	4	617261.697	5738040.678	1476.16
	5	617271.675	5738043.314	1476.12
	6	617281.32	5738046.312	1475.75
Transect 2				
	7	617254.689	5738028.225	1476.13
	3	617252.916	5738038.12	1476.98
	8	617265.12	5738031.784	1475.84
Transect 3				
	9	617265.12	5738031.784	1475.84
	4	617261.697	5738040.678	1476.16
	10	617258.056	5738050.055	1476.74
Transect 4				
	11	617276.94	5738036.105	1475.12
	5	617271.675	5738043.314	1476.12
	12	617265.915	5738052.141	1476.13

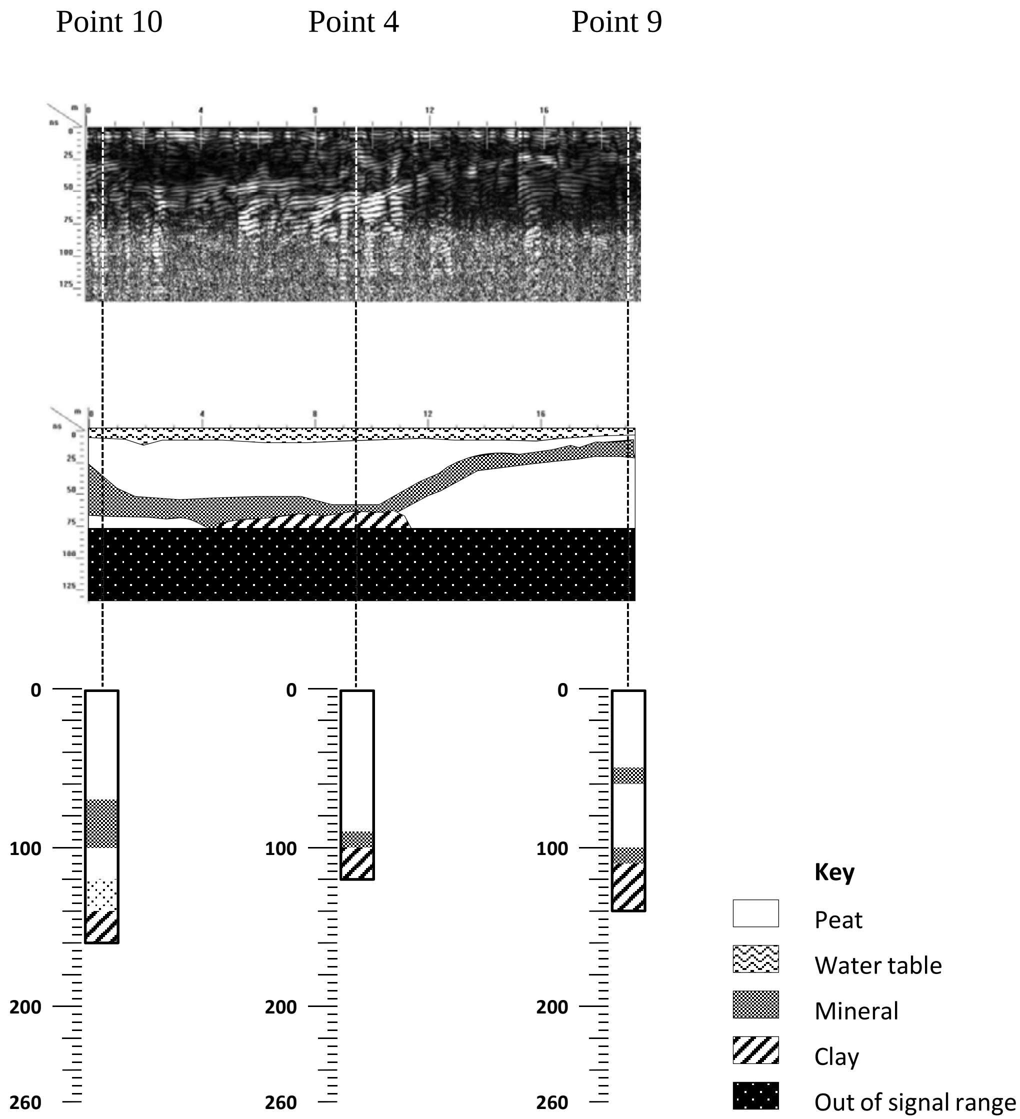
Site 490 transect 1



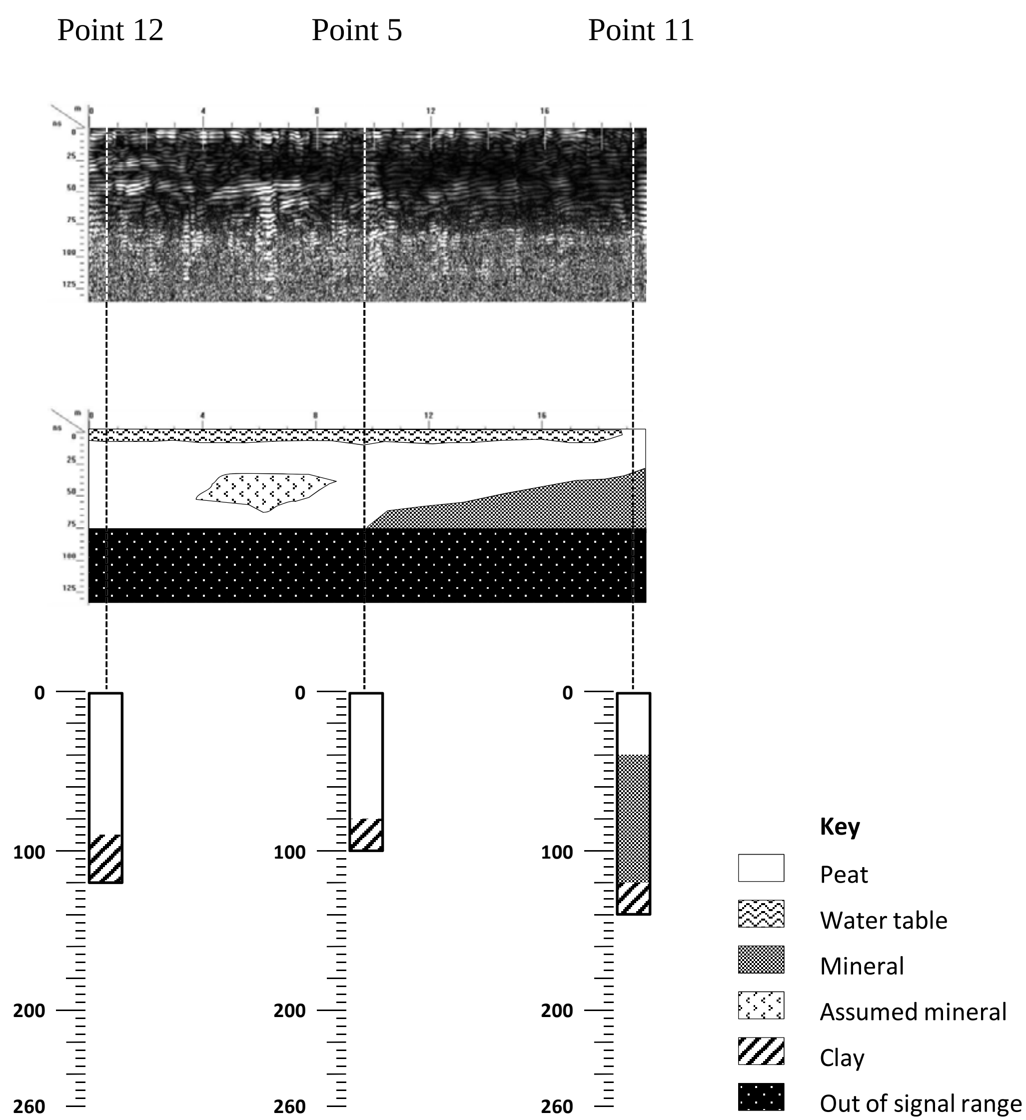
Site 490 transect 2



Site 490 transect 3



Site 490 transect 4



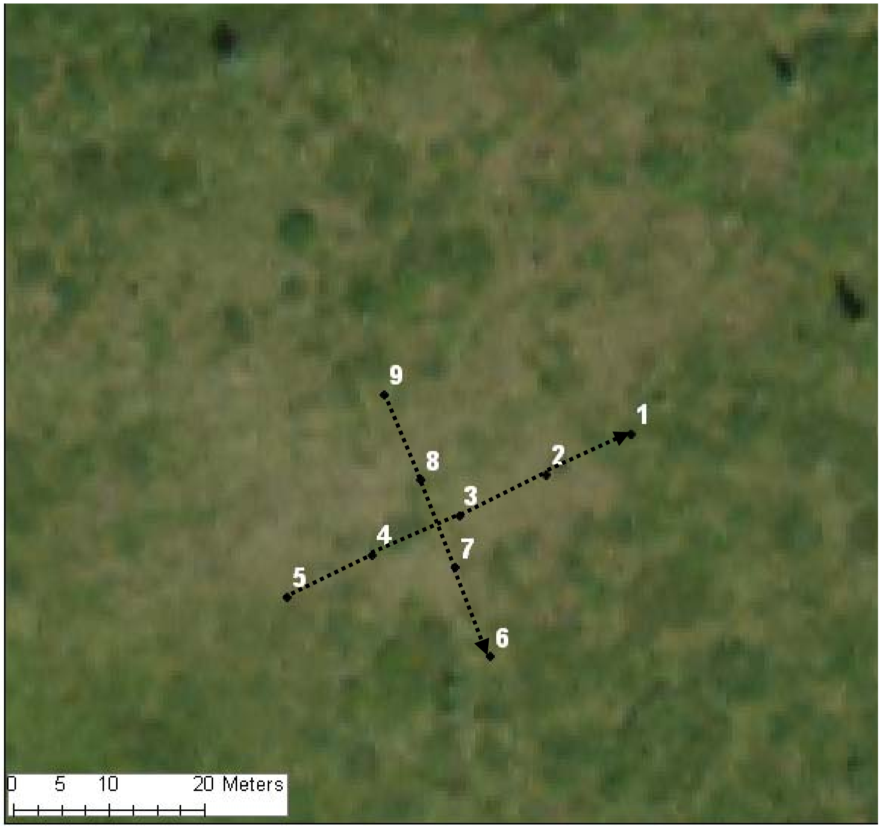
Site 510 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

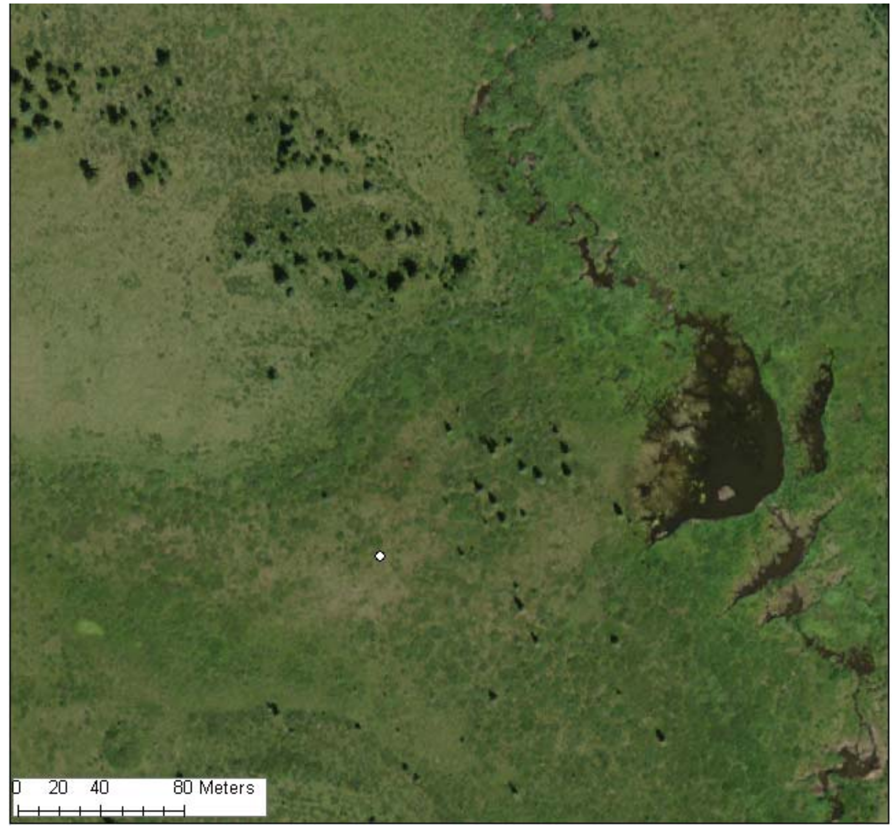
Radar	**Gain**
Antenna – 200MHz	Auto
Mode – Distance	Points – 5
Scan	**Filters**
Samples – 512	LP_IIR – 600
Format (bits) - 16	HP_IIR – 50
Range (ns) – 150	Stacking - 0
Rate - 64	
Scn/unit (m) – 50	
Gain (dB) – 0	

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 510 transect layout



Site 510 GPR location



Transect order

T1 – 5,4,3,2,1

T2 – 9,8,7,6

——— Continuous peat/ mineral layering

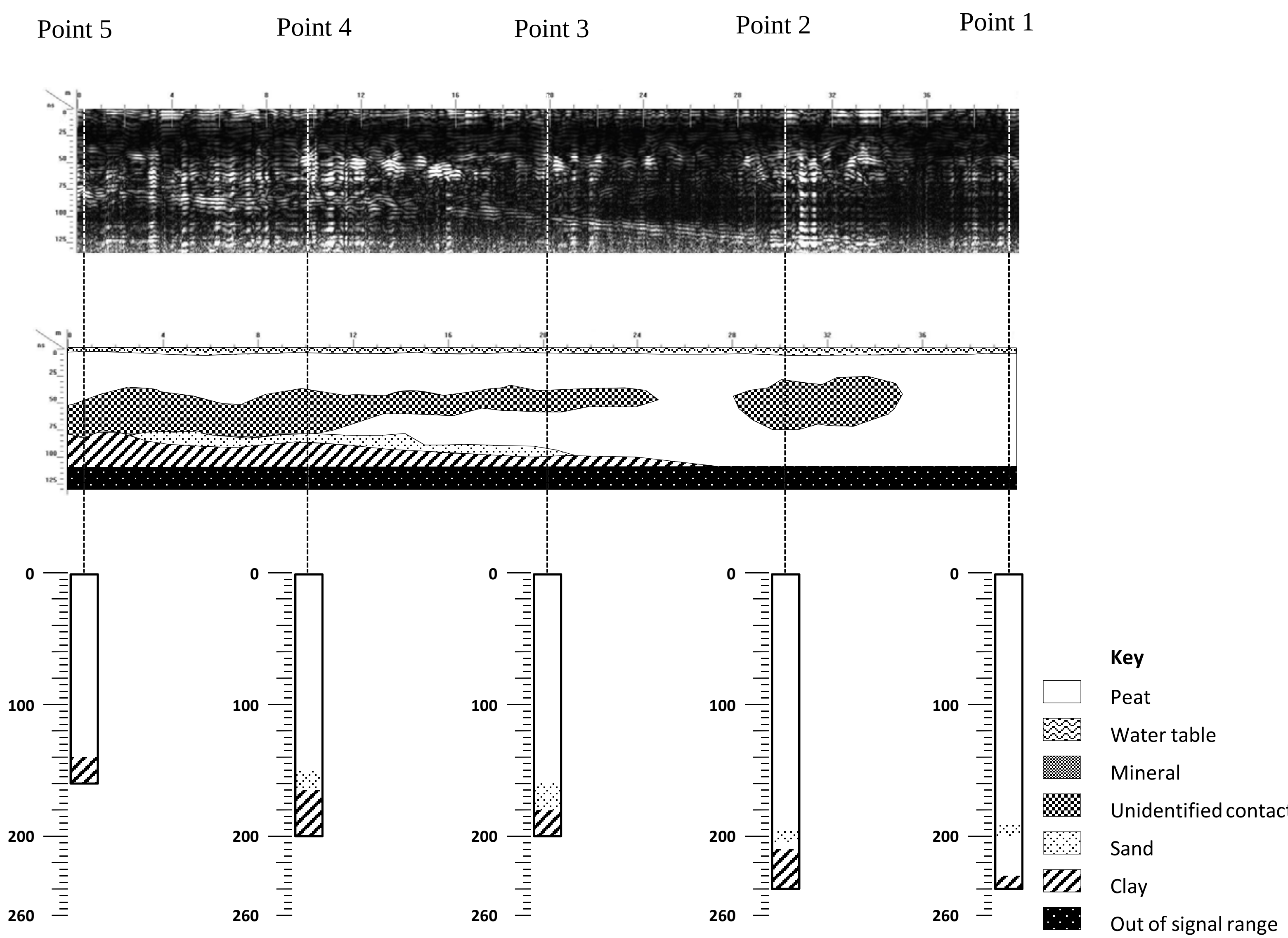
– – – Discontinuous peat/ mineral layering

.... No peat/mineral layering

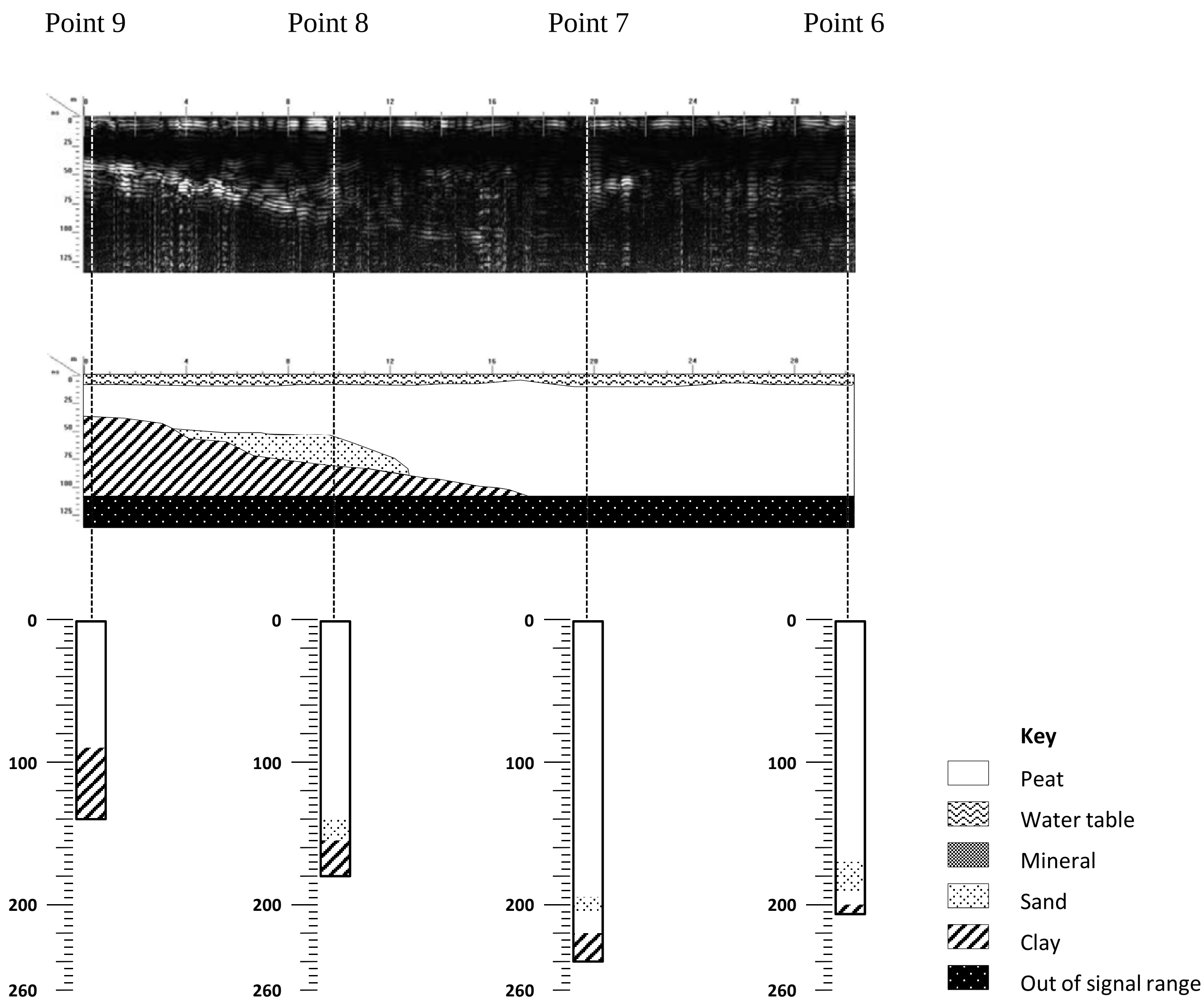
GPS data

Site 510				
		UTM		
	Point	**X**	**Y**	**Elevation**
Transect 1				
	1	5656450.61	655507.111	1397.532
	2	5656446.4	655498.143	1397.592
	3	5656442.03	655489.03	1397.801
	4	5656437.99	655479.952	1397.712
	5	5656433.53	655470.969	1397.501
Transect 2				
	6	5656427.21	655492.326	1396.928
	7	5656436.58	655488.634	1397.142
	8	5656445.81	655485.026	1397.38
	9	5656454.75	655481.209	1397.414

Site 510 transect 1



Site 510 transect 2



Site 524 GPR survey

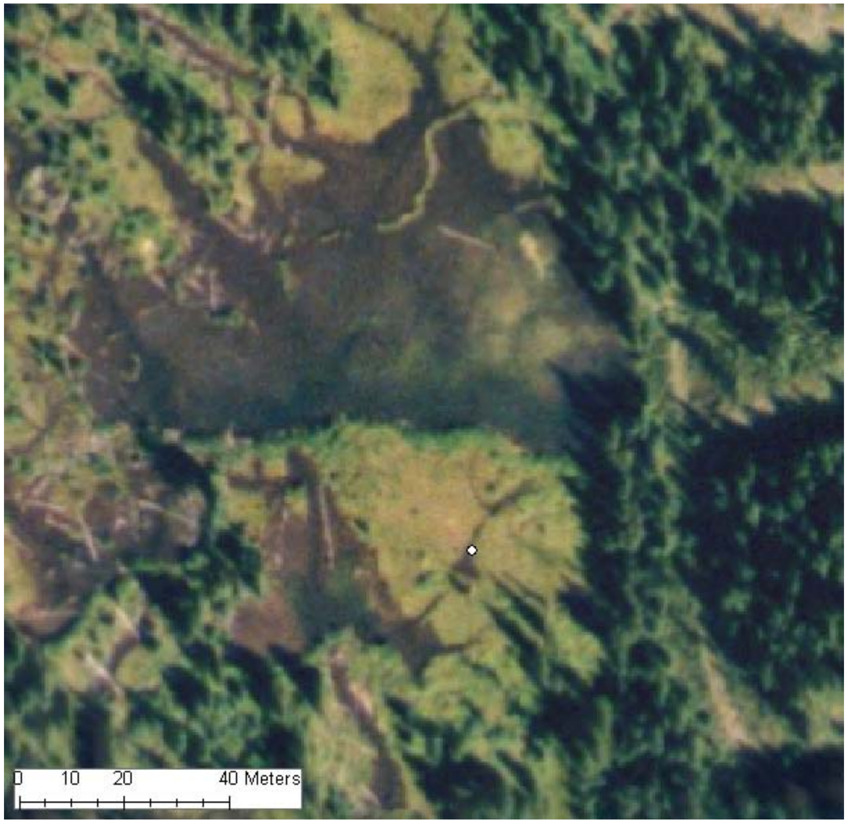
The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 5
Scan Samples – 512 Format (bits) - 16 Range (ns) – 150 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 524 transect layout

Site 524 GPR location



Transect order

T1 – 4,3,6,2,1

T2 – 7,6,5

T3 – 10,9,8

T4 – 12,9,11

Continuous peat/ mineral layering

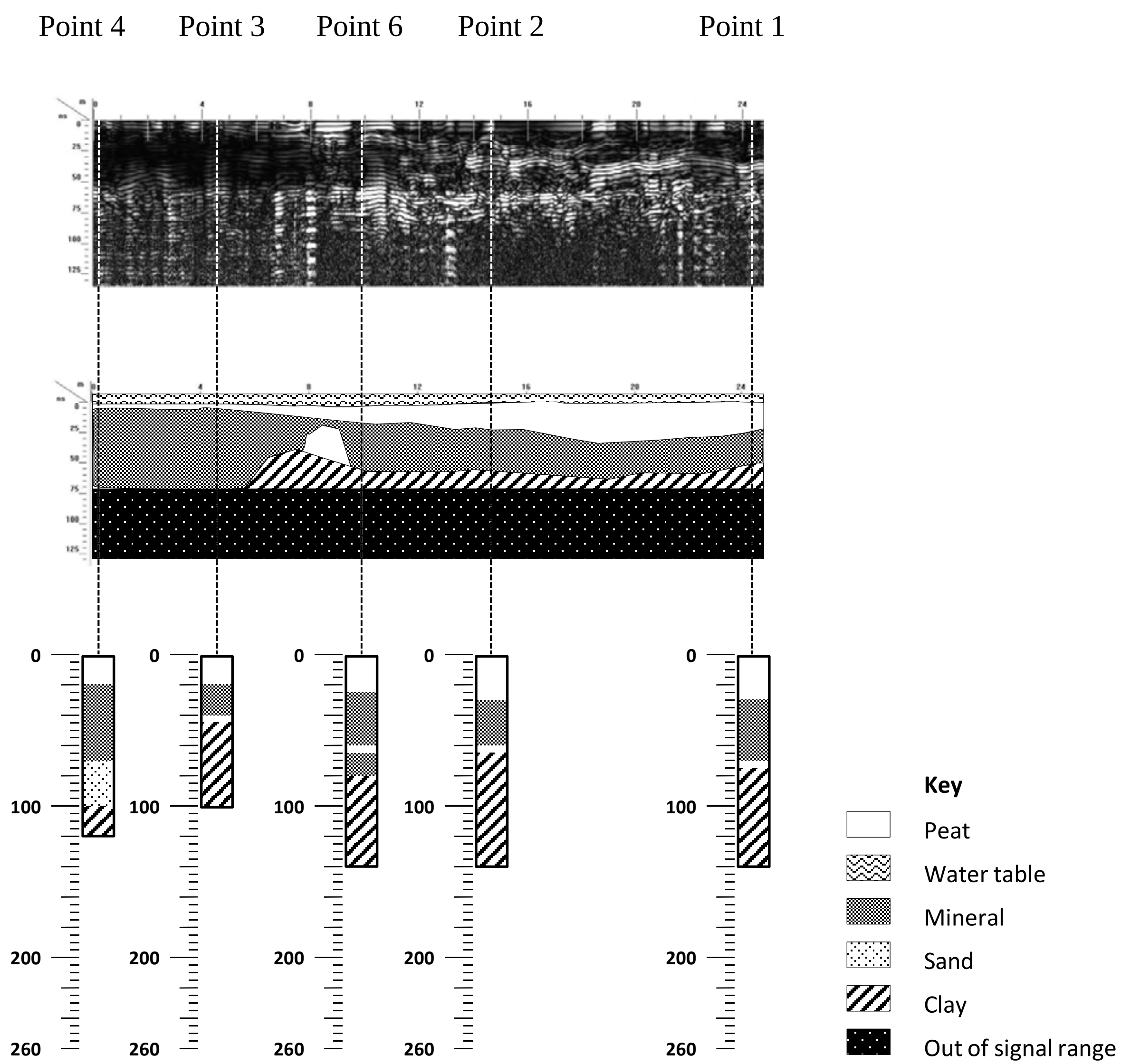
Discontinuous peat/ mineral layering

No peat/mineral layering

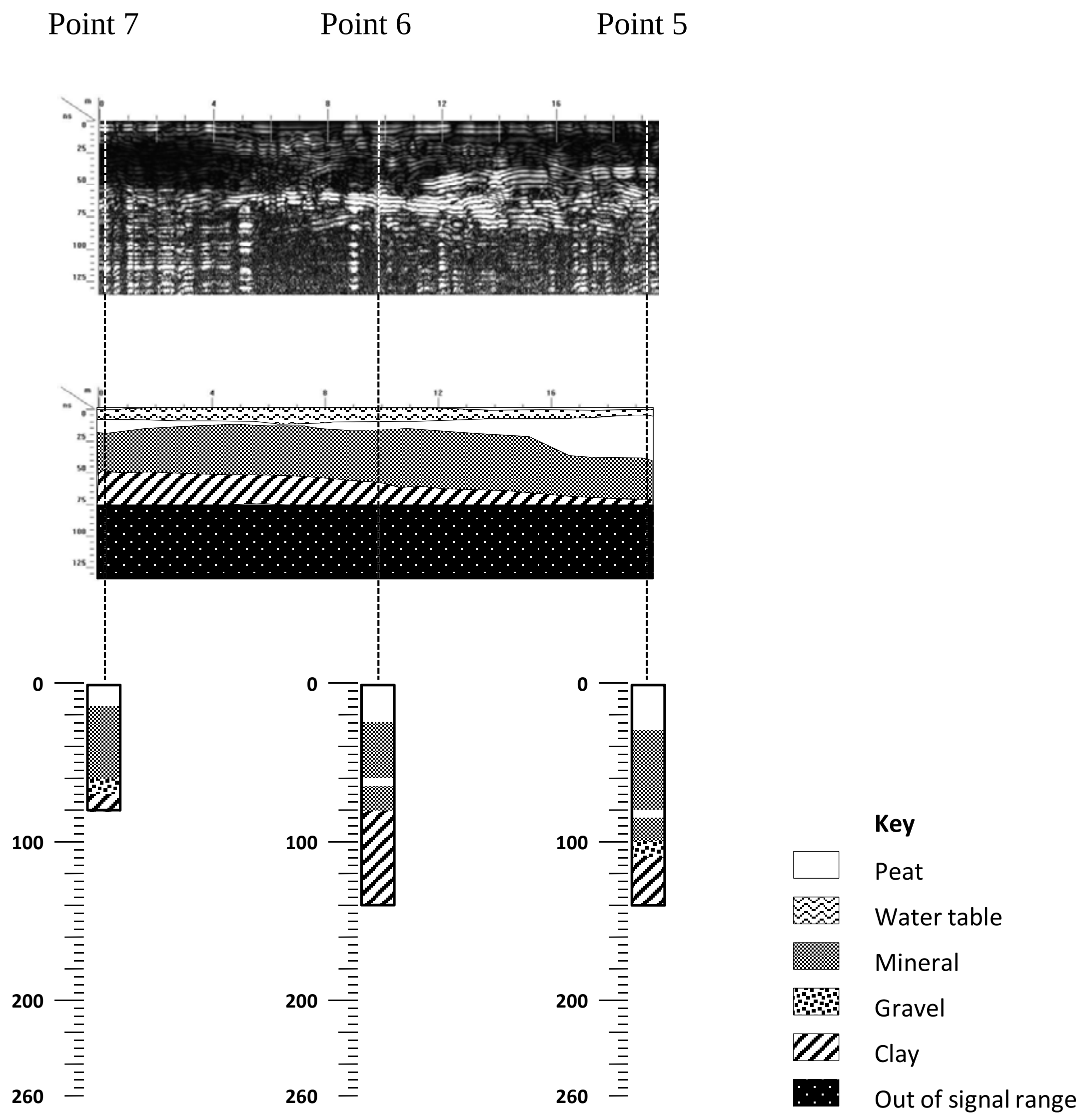
GPS data

		UTM		
	Point	**X**	**Y**	**Elevation**
Transect 1				
	1	5596852.1	654619	Not recorded
	2	5596842.6	654616.1	Not recorded
	6	5596837.9	654615.7	Not recorded
	3	5596833.1	654613.9	Not recorded
	4	5596828.2	654613.3	Not recorded
Transect 2				
	5	5596837.4	654625.2	Not recorded
	6	5596837.9	654615.7	Not recorded
	7	5596839.8	654604.9	Not recorded
Transect 3				
	8	5596839.5	654632.5	Not recorded
	9	5596829.9	654634.1	Not recorded
	10	5596820	654634.1	Not recorded
Transect 4				
	11	5596826.8	654639.7	Not recorded
	9	5596829.9	654634.1	Not recorded
	12	5596831.8	654630.2	Not recorded

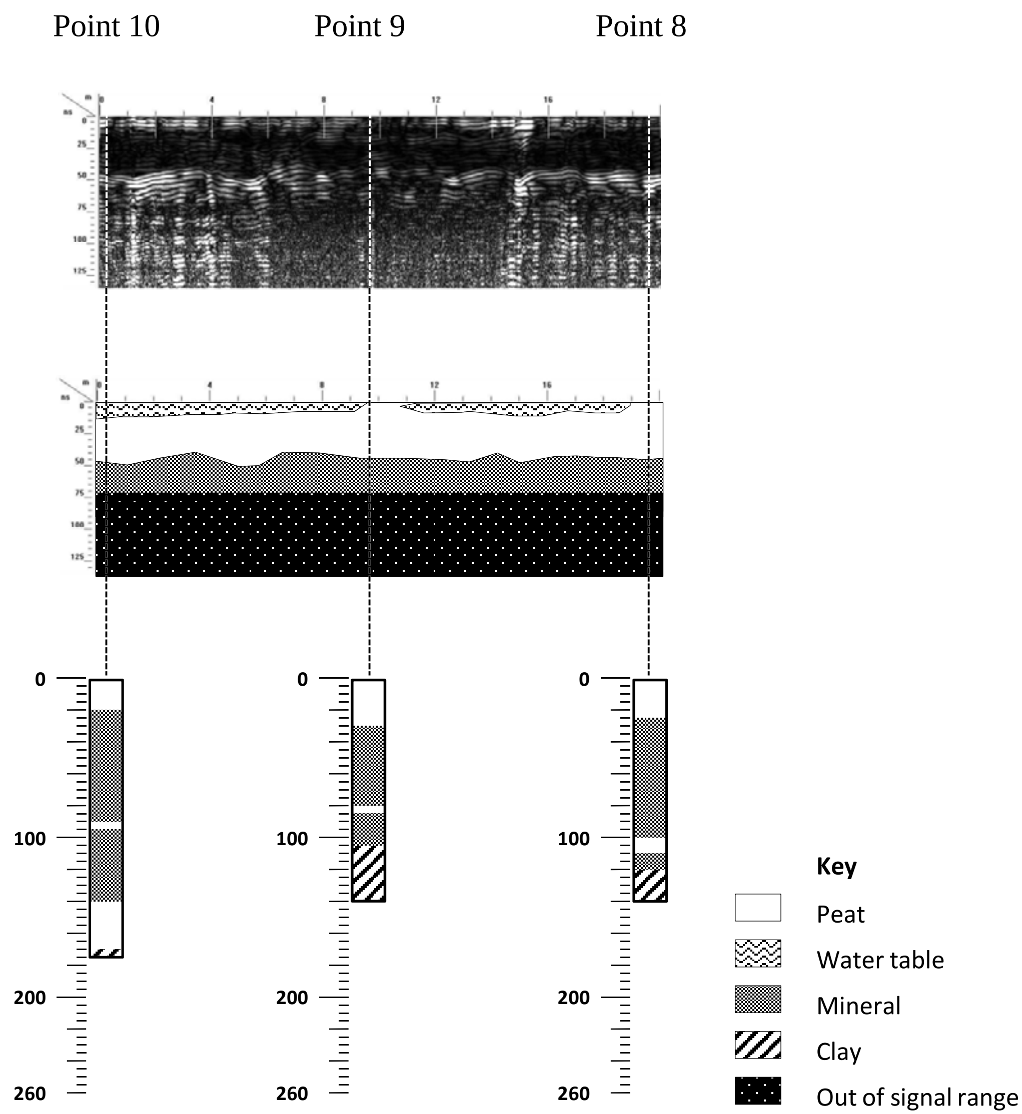
Site 524 transect 1



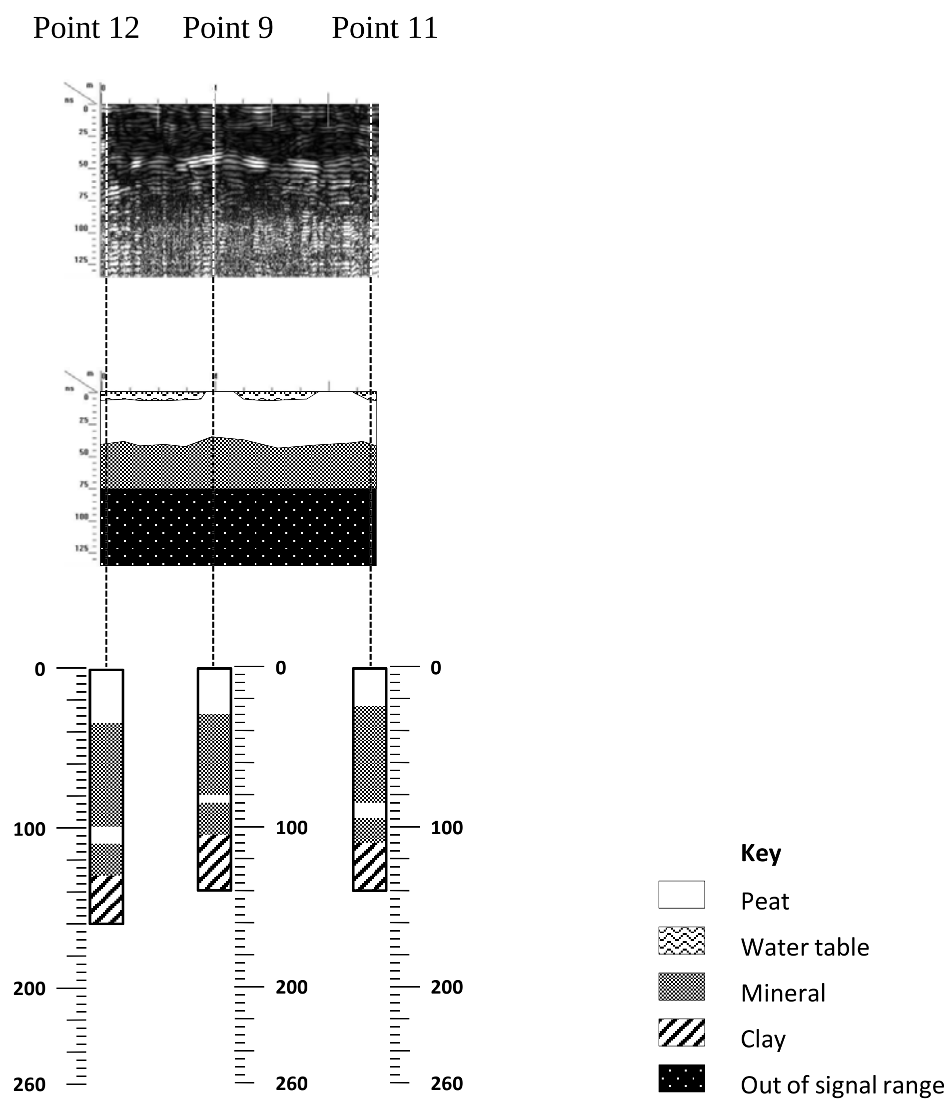
Site 524 transect 2



Site 524 transect 3



Site 524 transect 4



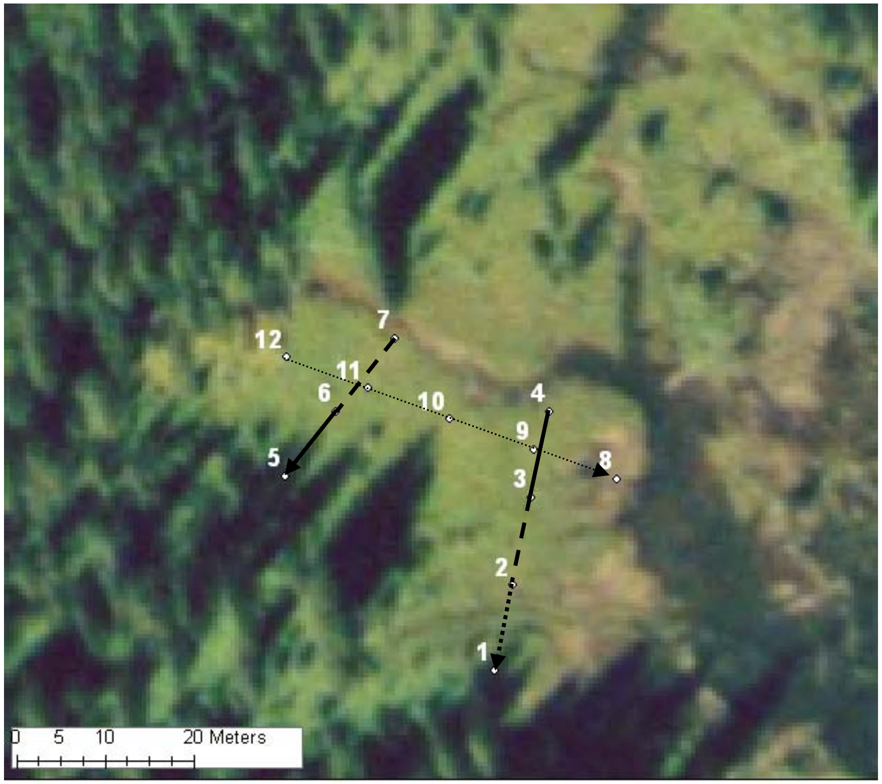
Site 559 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 5
Scan Samples – 512 Format (bits) - 16 Range (ns) – 150 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 559 transect layout



Site 559 GPR location

Transect order

T1 – 4,3,2,1

T2 – 7,6,5

T3 – 12,11,10,9,8

Continuous peat/ mineral layering

Discontinuous peat/ mineral layering

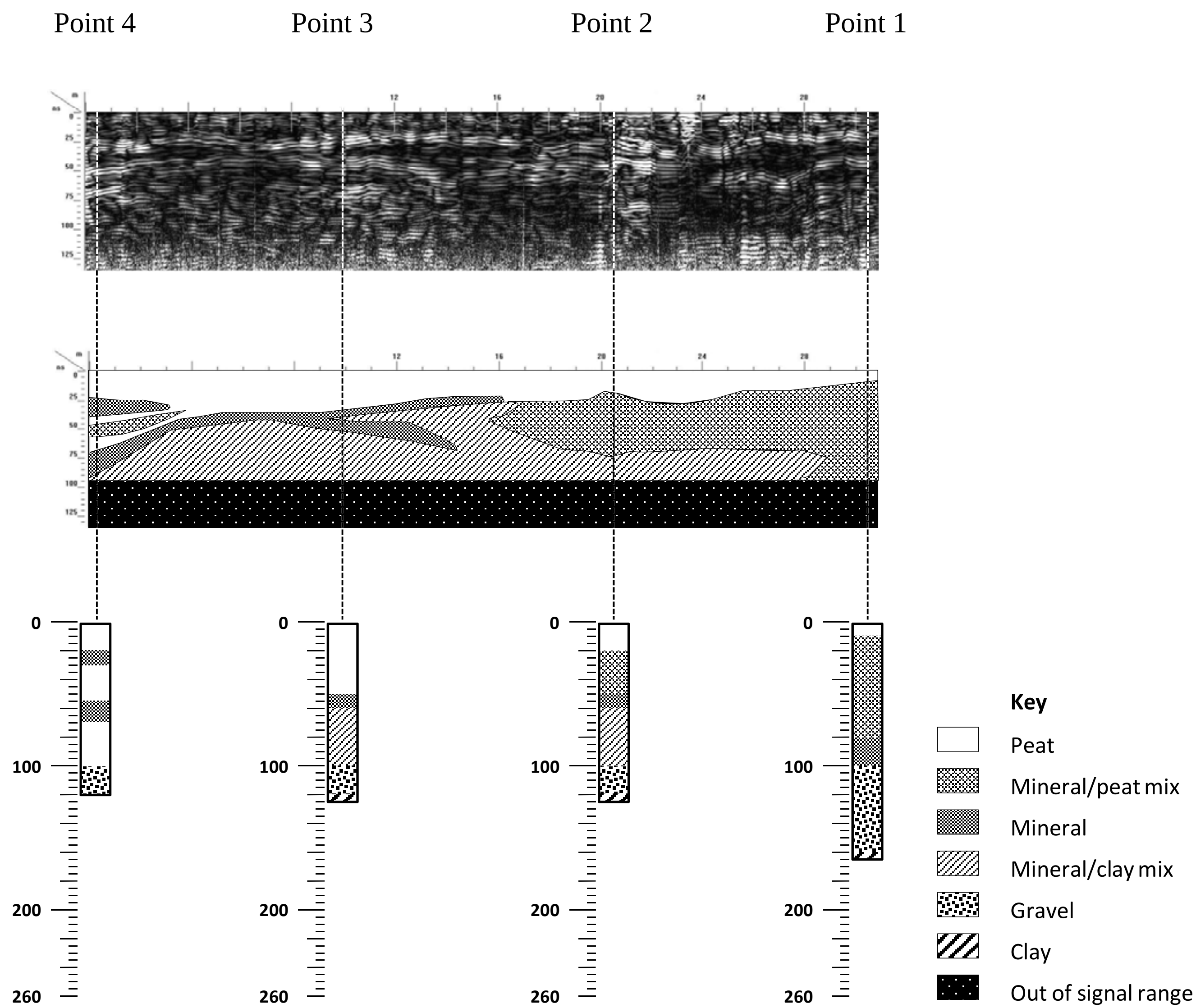
No peat/mineral layering

Uninterpreted transect

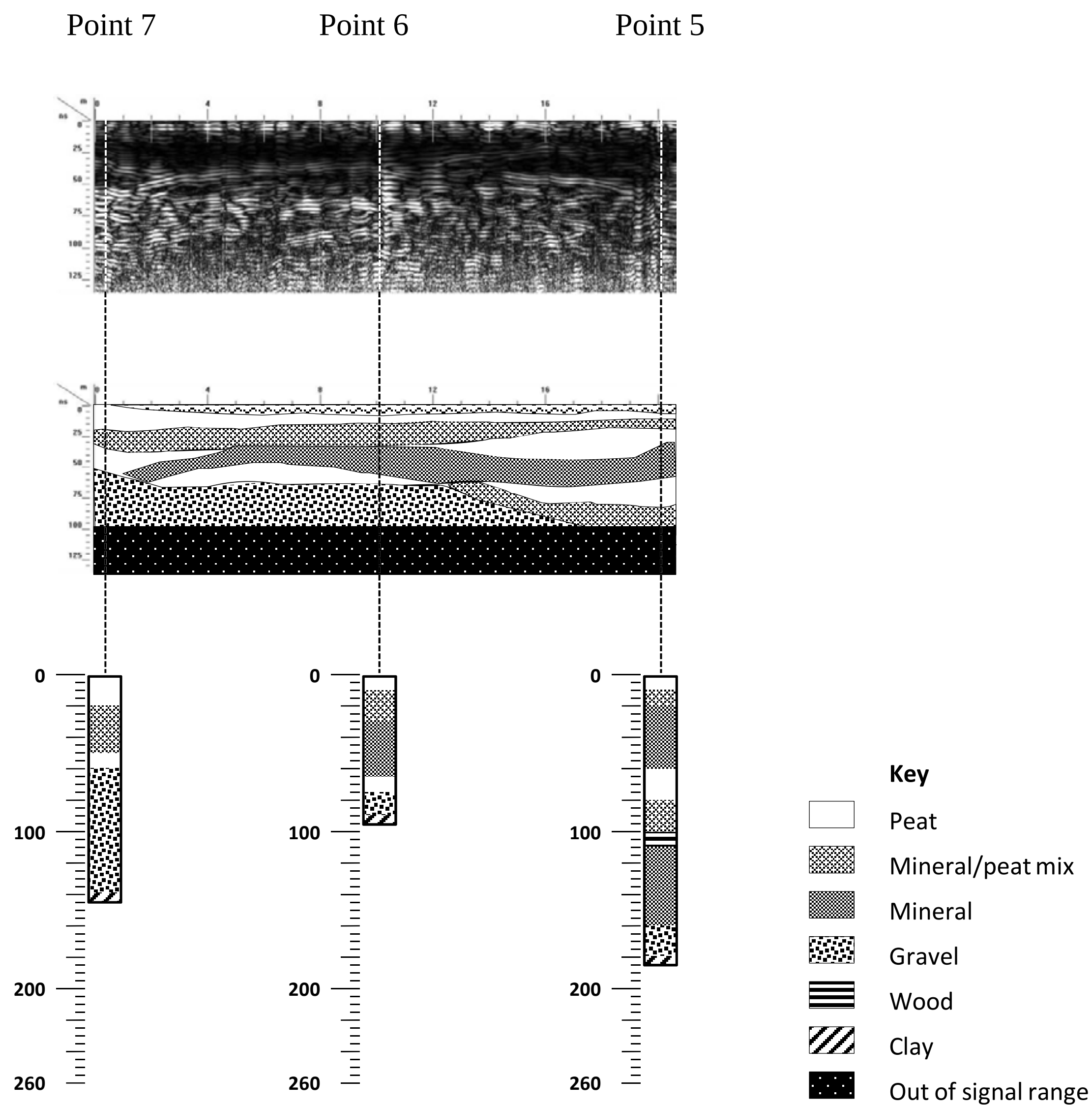
GPS data

Site 559				
		UTM		
	Point	**X**	**Y**	**Elevation**
Transect 1				
	1	5620480.91	625783.774	1769.524
	2	5620490.48	625785.84	1768.829
	3	5620500.45	625787.912	1769.214
	4	5620510.1	625790.088	1769.075
Transect 2				
	5	5620502.77	625760.123	1769.901
	6	5620510.09	625765.913	1770.364
	7	5620518.33	625772.557	1770.036
Transect 3				
	8	5620502.46	625797.635	1769.832
	9	5620505.77	625788.342	1770.492
	10	5620509.22	625778.794	1770.662
	11	5620512.7	625769.503	1770.733
	12	5620516.18	625760.291	1771.957

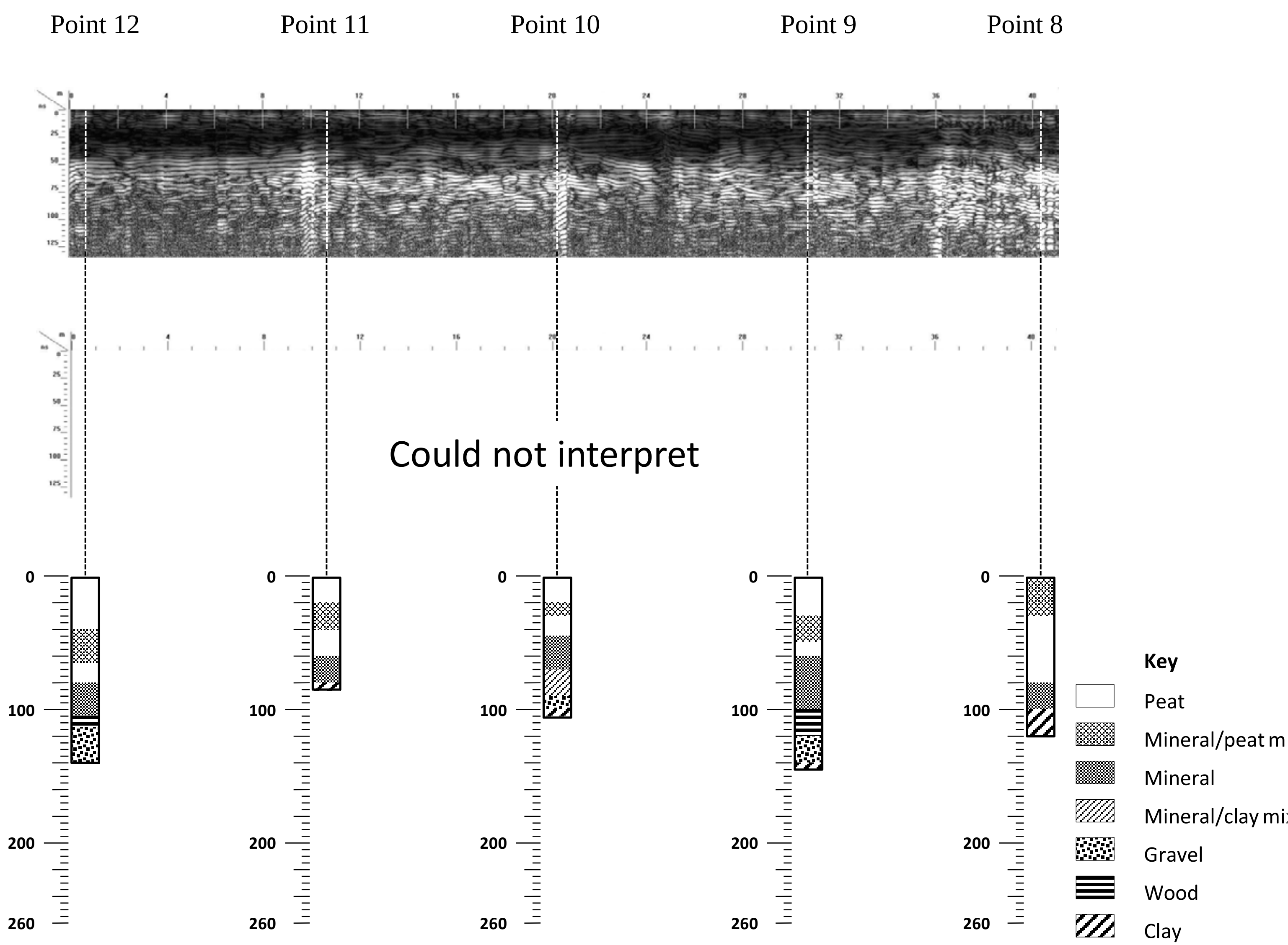
Site 559 transect 1



Site 559 transect 2



Site 559 transect 3



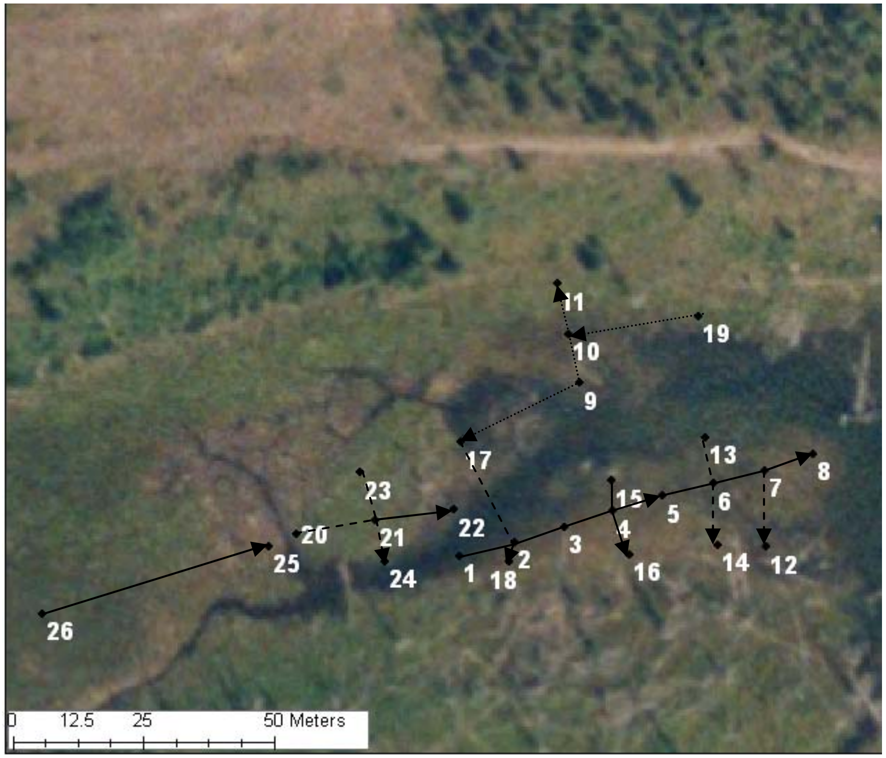
Site 903 GPR survey

The following settings were applied on the control unit of the GSSI ground penetrating radar system. These are listed in the same order as on the menu system on the unit. Only menu items that were changed for the survey are listed here. Unchanged items remained at the factory settings.

Radar Antenna – 200MHz Mode – Distance	**Gain** Auto Points – 3
Scan Samples – 1024 Format (bits) - 16 Range (ns) – 200 Rate - 64 Scn/unit (m) – 50 Gain (dB) – 0	**Filters** LP_IIR – 600 HP_IIR – 50 Stacking - 0

The system used a survey wheel to measure horizontal distance and calibrate the number of scans per unit. This calibration was carried out in accordance with the instruction manual and using a 20m distance over a typical area of the survey site.

Site 903 transect layout



Site 903 GPR location

Transect order		
T1a – 1,2,3,4,5	T5 – 15,4,16	T10 – 23,21,24
T1b – 5,6,7,8	T6 – 17,2,18	T11 – 26,25
T2 – 9,10,11	T7 – 9,17	
T3 – 7,12	T8 – 19,10	
T4 – 13,6,14	T9 – 20,21,22	

Continuous peat/ mineral layering

Discontinuous peat/ mineral layering

No peat/mineral layering

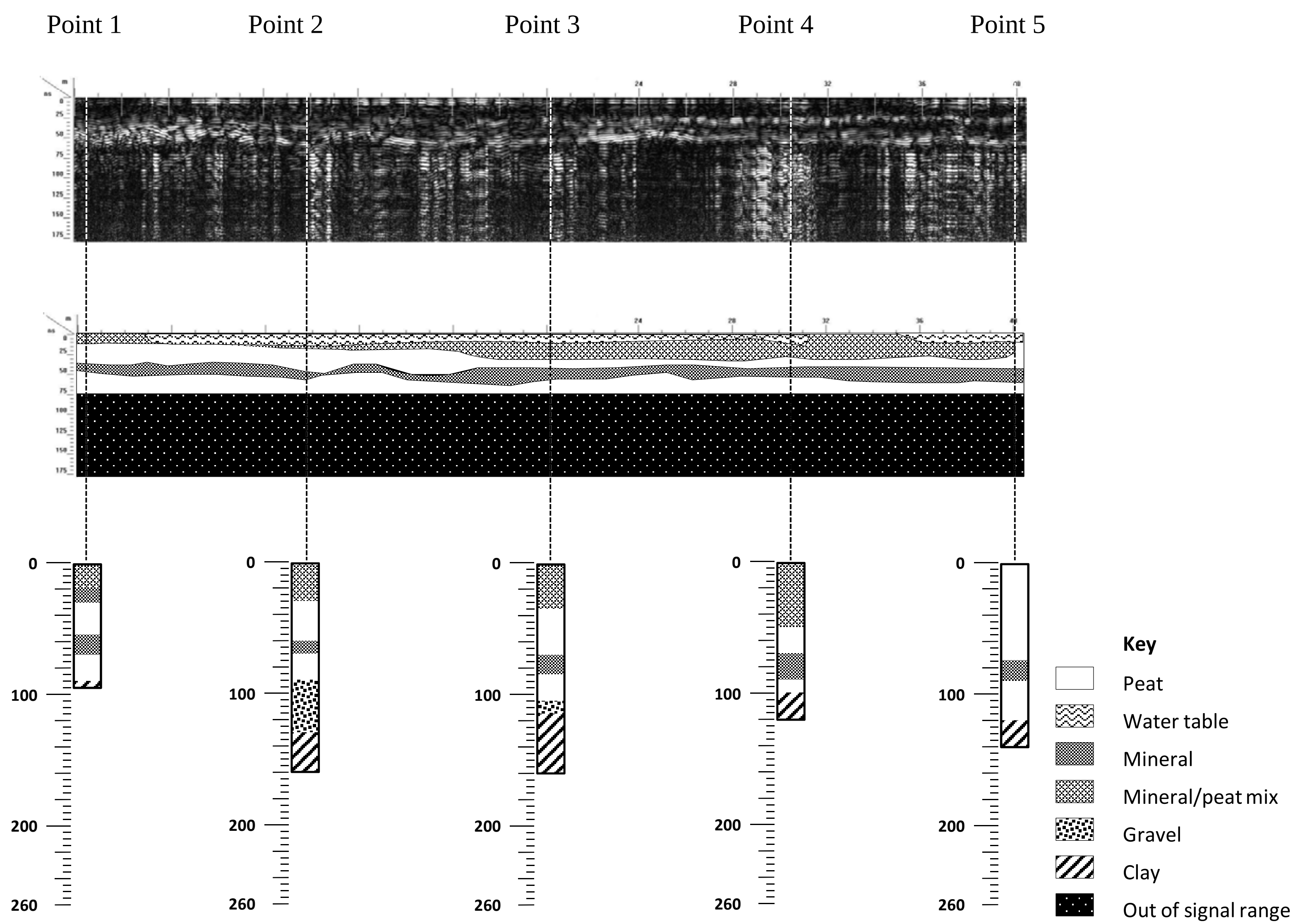
GPR data

		UTM		
	Point	**X**	**Y**	**Elevation**
Transect 1				
	1	5664867.83	633925.634	1348.83
	2	5664870.5	633935.997	1349.853
	3	5664873.44	633945.635	1349.39
	4	5664876.42	633954.901	1349.636
	5	5664879.28	633964.557	1349.274
	6	5664881.73	633974.241	1348.781
	7	5664884.26	633984.087	1349.688
	8	5664887.4	633993.406	1348.939
Transect 2				
	9	5664901.09	633948.629	1350.365
	10	5664910.37	633946.535	1349.653
	11	5664920.08	633944.203	1349.954
Transect 3				
	7	5664884.26	633984.087	1349.688
	12	5664869.54	633984.338	1349.531
Transect 4				
	13	5664890.61	633972.551	1349.743
	6	5664881.73	633974.241	1348.781
	14	5664868.05	633958.036	1349.739
Transect 5				
	15	5664889.6	633925.746	1350.314
	5	5664879.28	633964.557	1349.274
	16	5664866.67	633934.965	1350.055

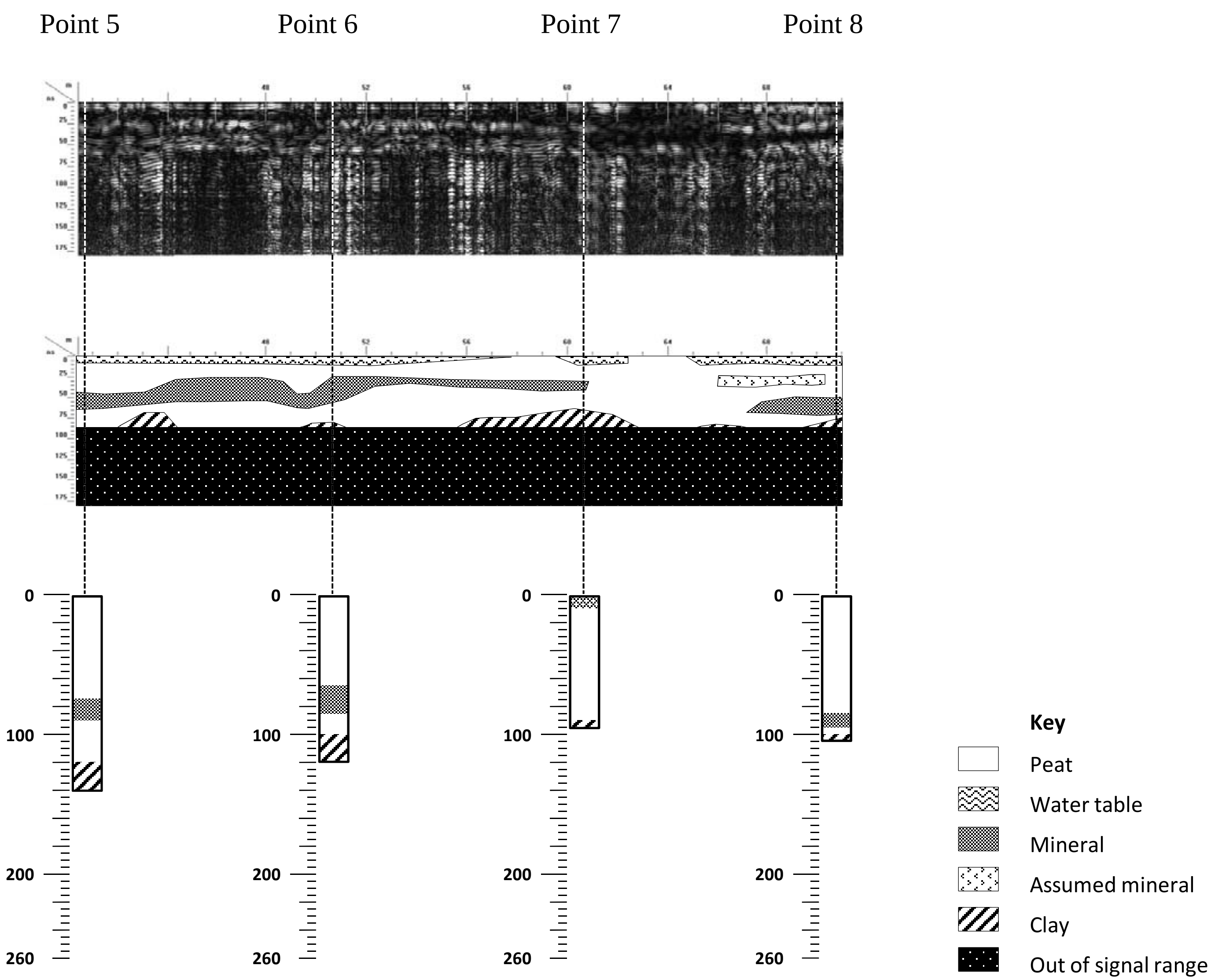
GPR data continued

Site 903				
		UTM		
	Point	**X**	**Y**	**Elevation**
Transect 6				
	17	5664913.87	633971.247	1348.918
	3	5664873.44	633945.635	1349.39
	18	5664876.66	633924.516	1348.529
Transect 7				
	9	5664901.09	633948.629	1350.365
	17	5664913.87	633971.247	1348.918
Transect 8				
	19	5664874.66	633909.438	1348.845
	10	5664910.37	633946.535	1349.653
Transect 9				
	20	5664883.82	633906.523	1349.325
	21	5664866.73	633911.14	1349.378
	22	5664869.7	633889.074	1349.964
Transect 10				
	23	5664856.69	633845.753	1350.851
	21	5664866.73	633911.14	1349.378
	24	5664865.7*	633410.8*	Not recorded
Transect 11				
	25	5664856*	633844.8*	Not recorded
	26	5664868.9*	633887.5*	Not recorded
* Uncorrected coordinate				

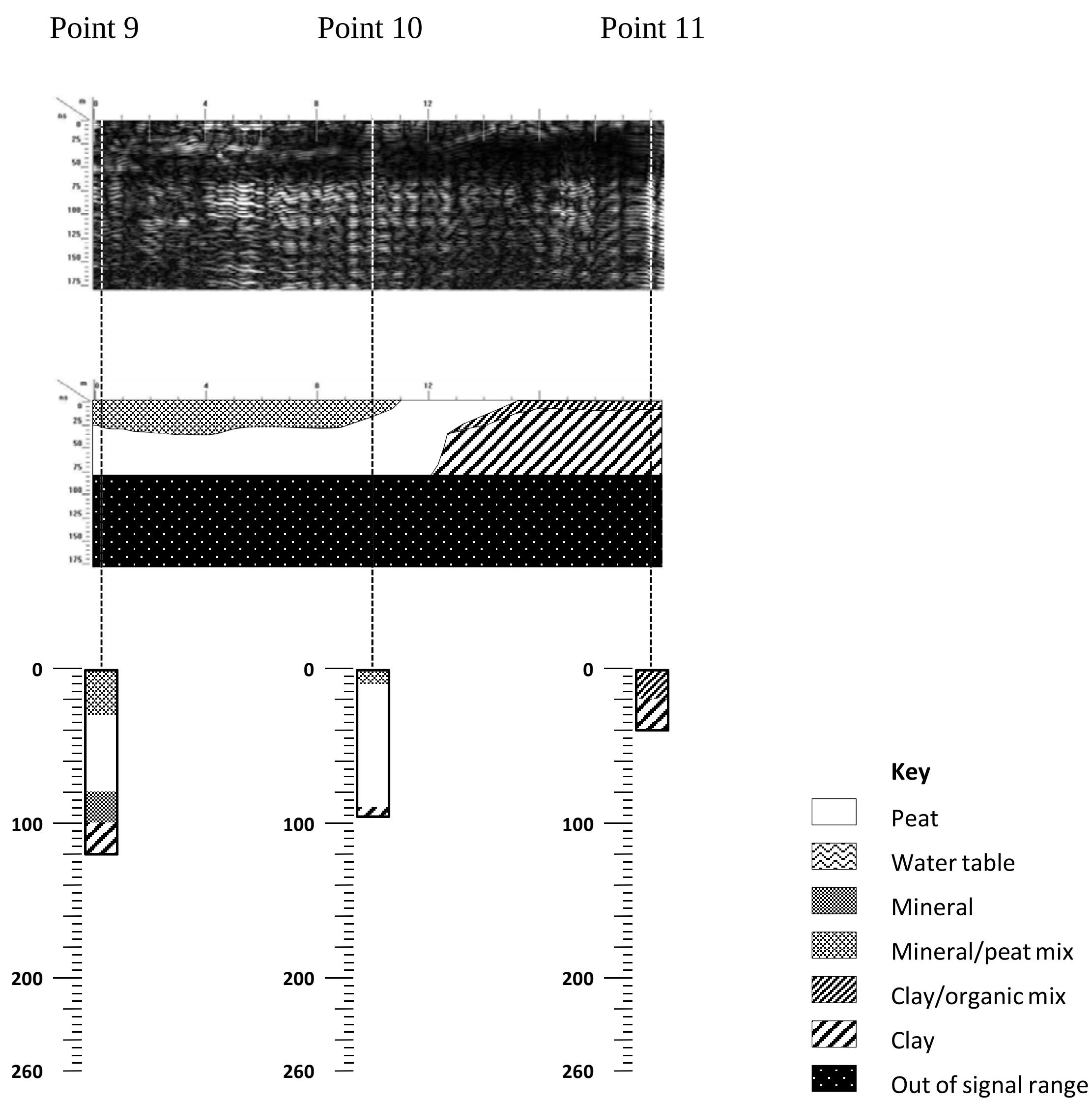
Site 903 transect 1a



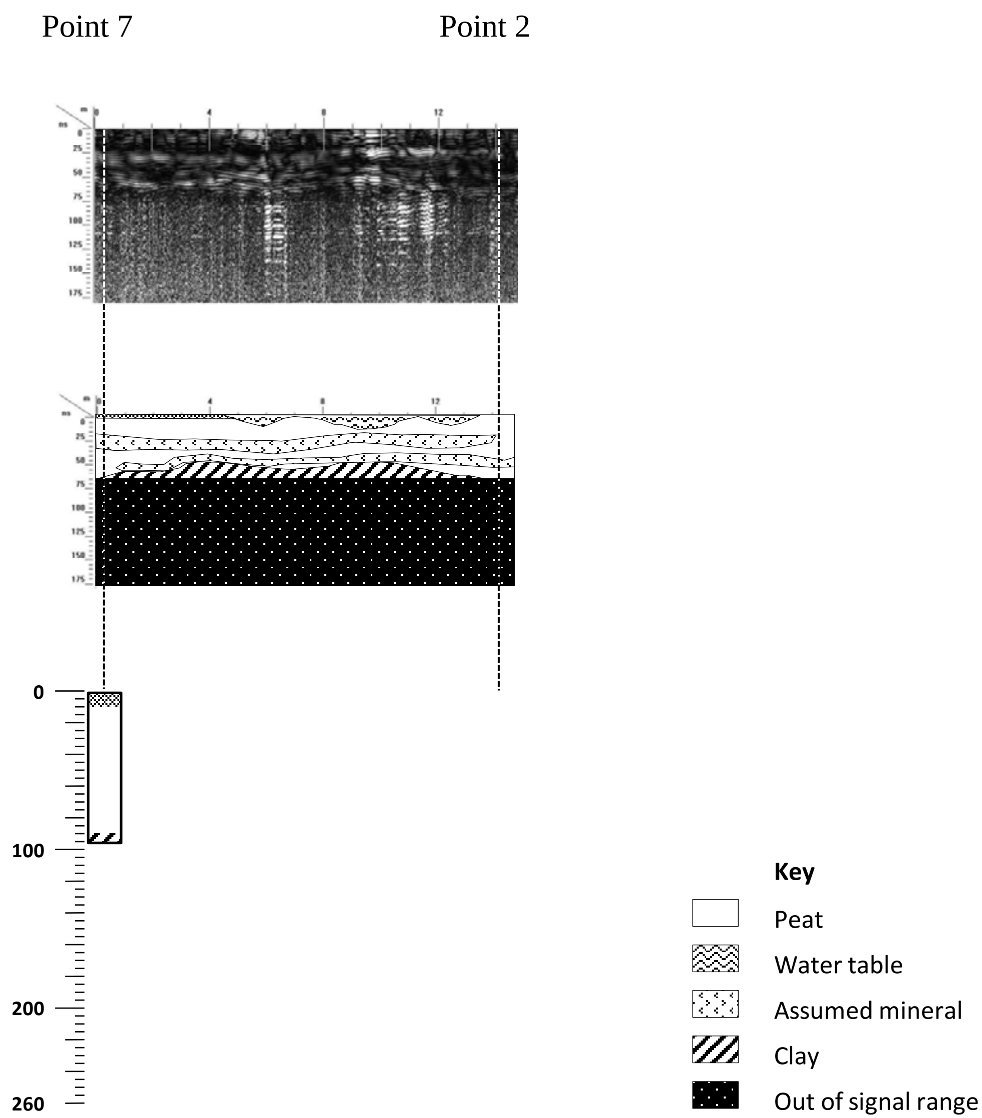
Site 903 transect 1b



Site 903 transect 2



Site 903 transect 3



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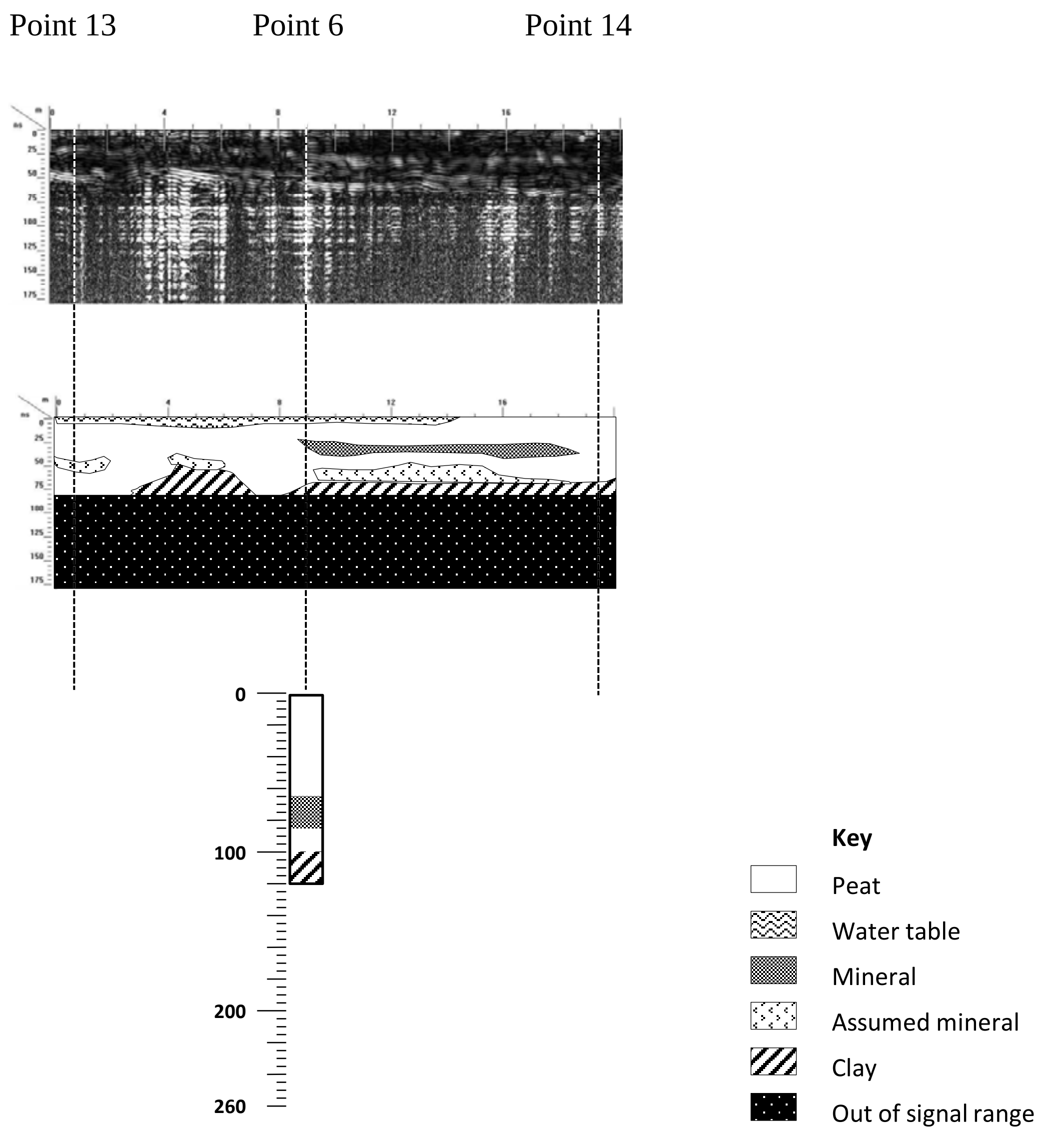

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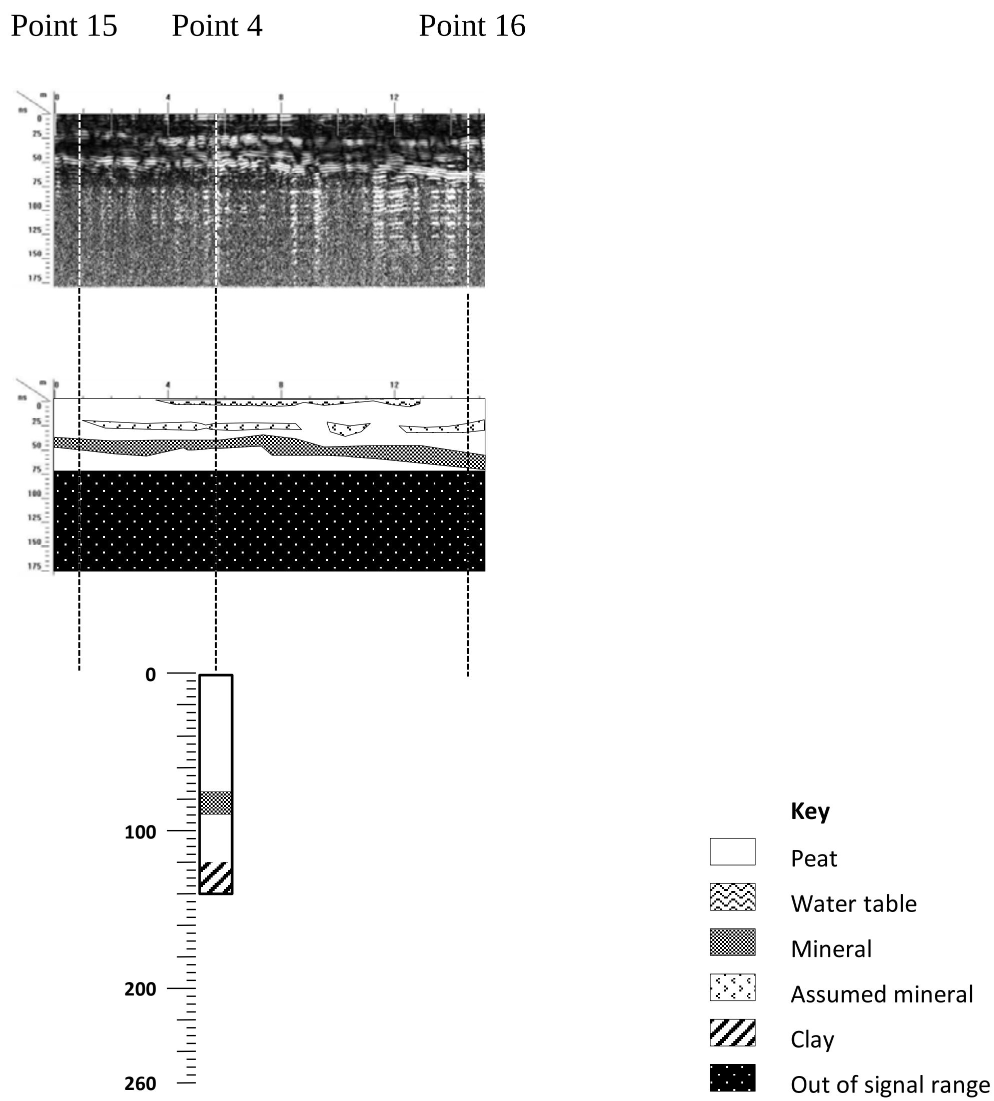

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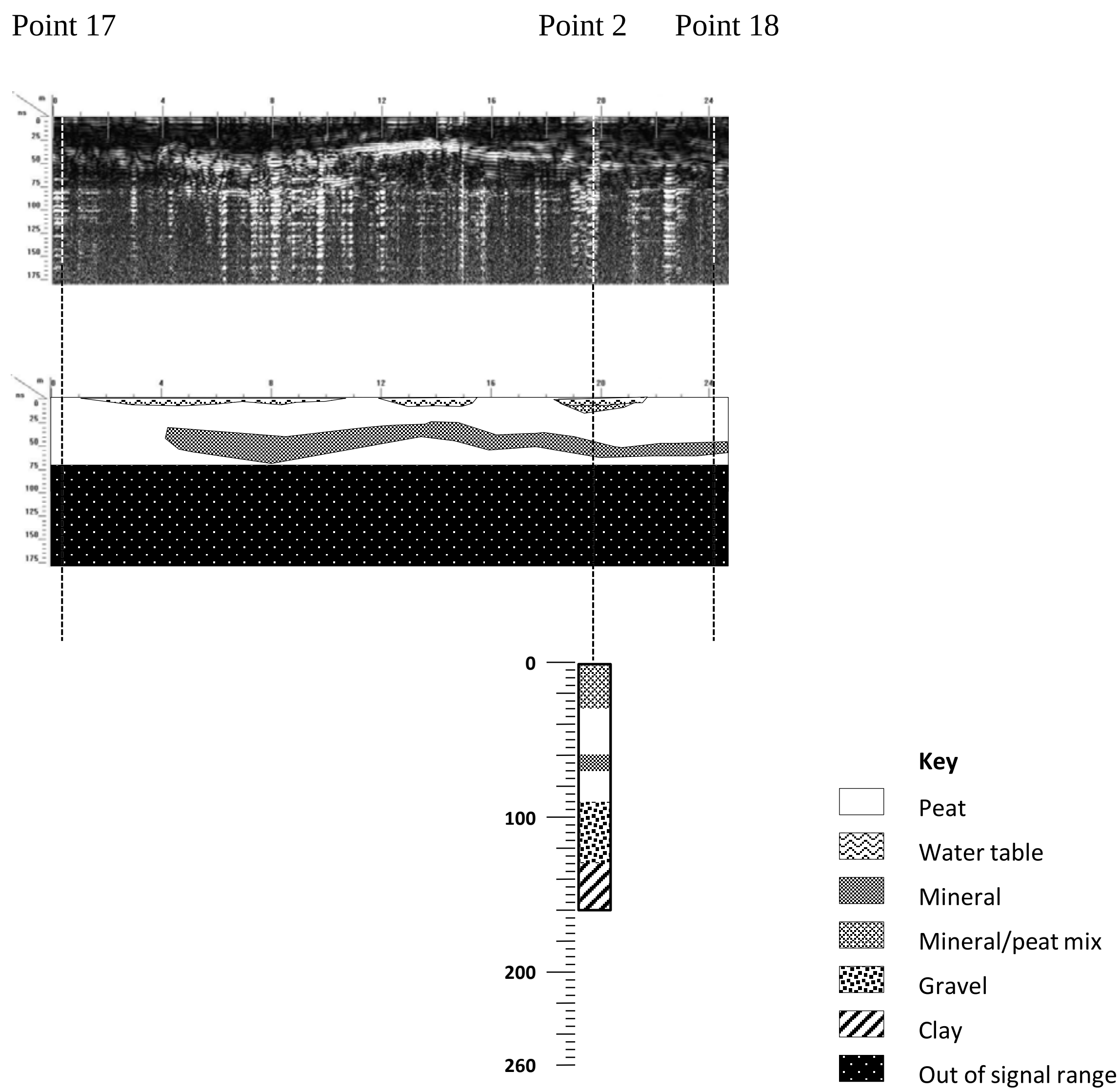

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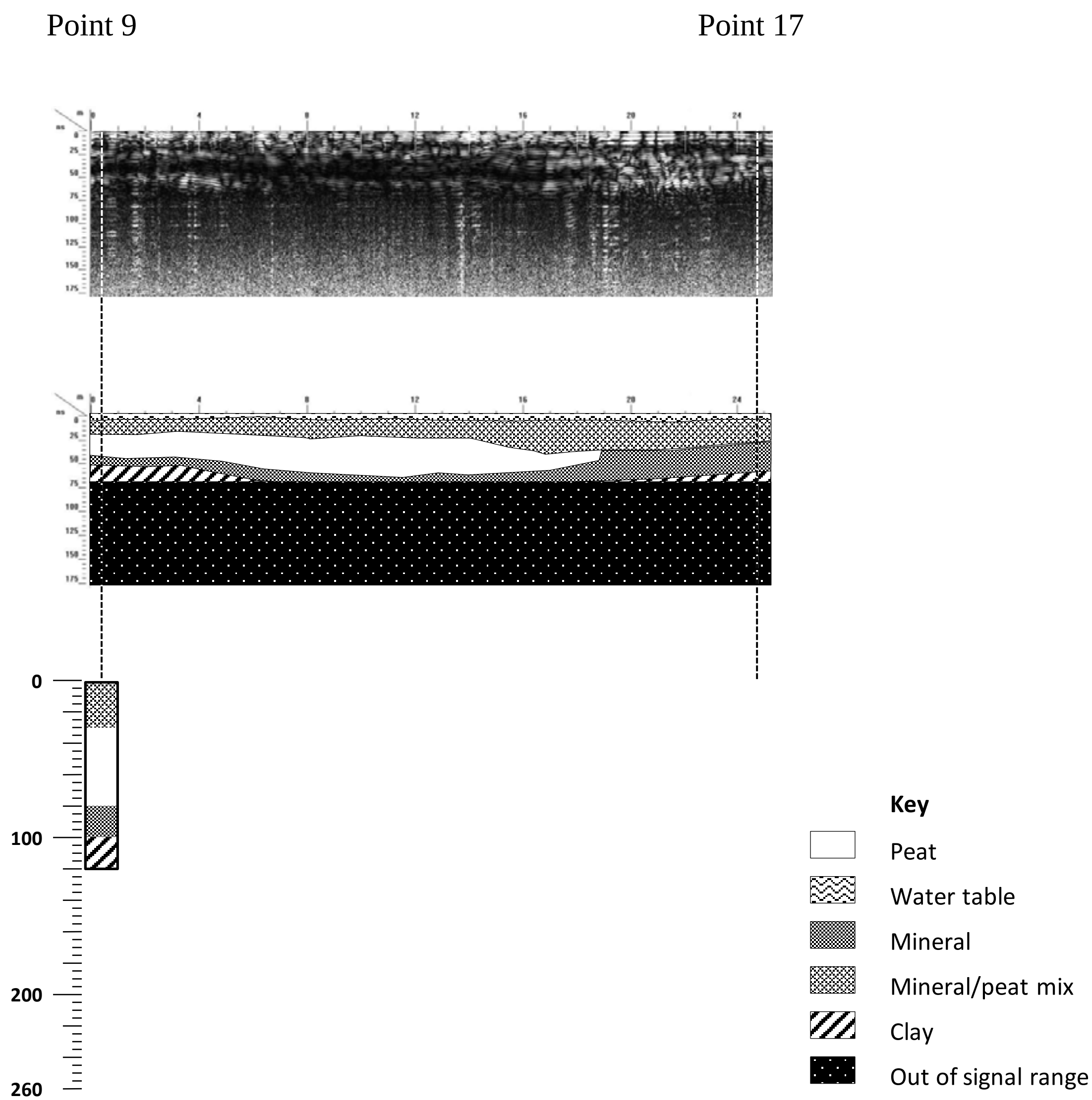

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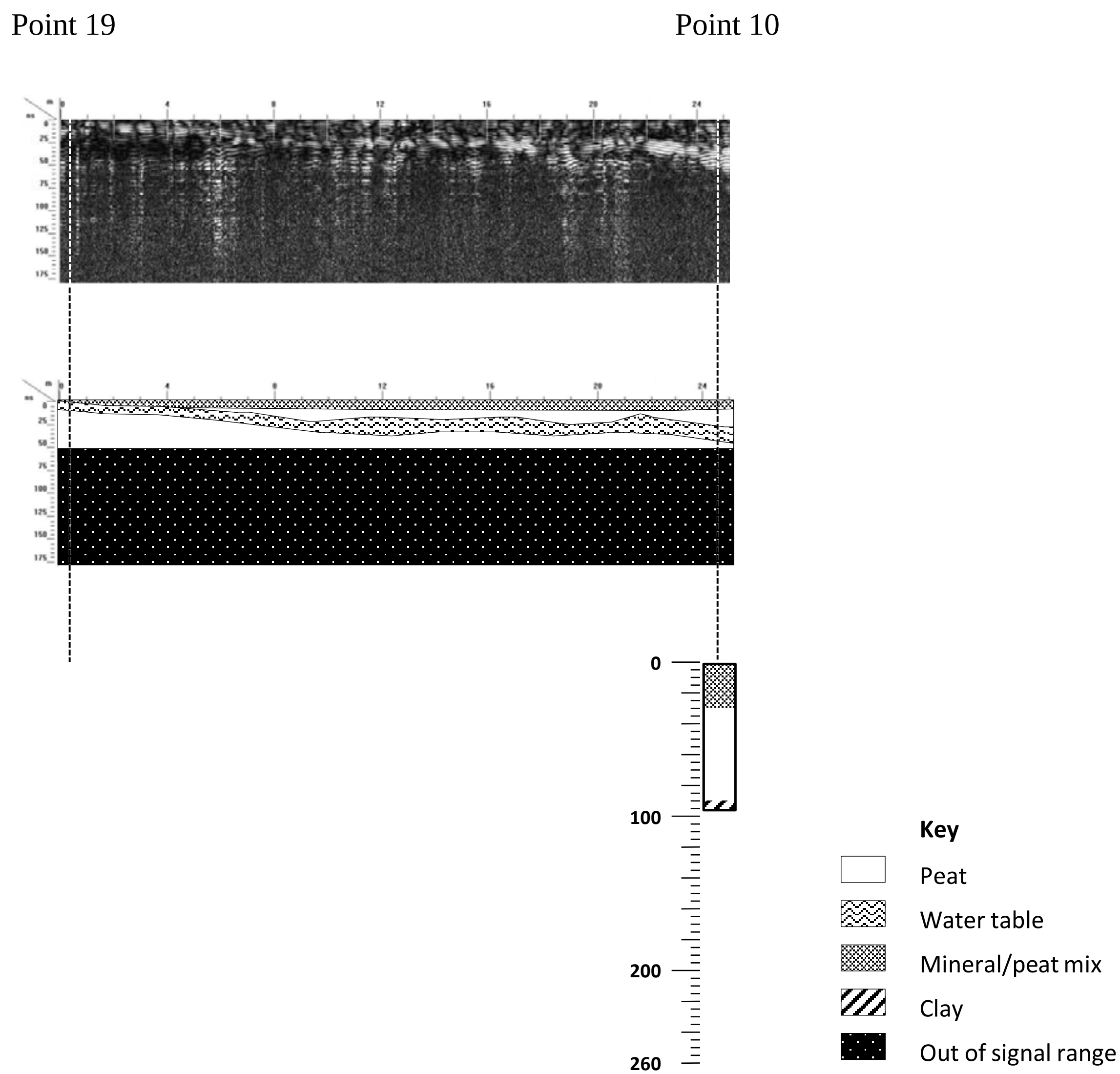

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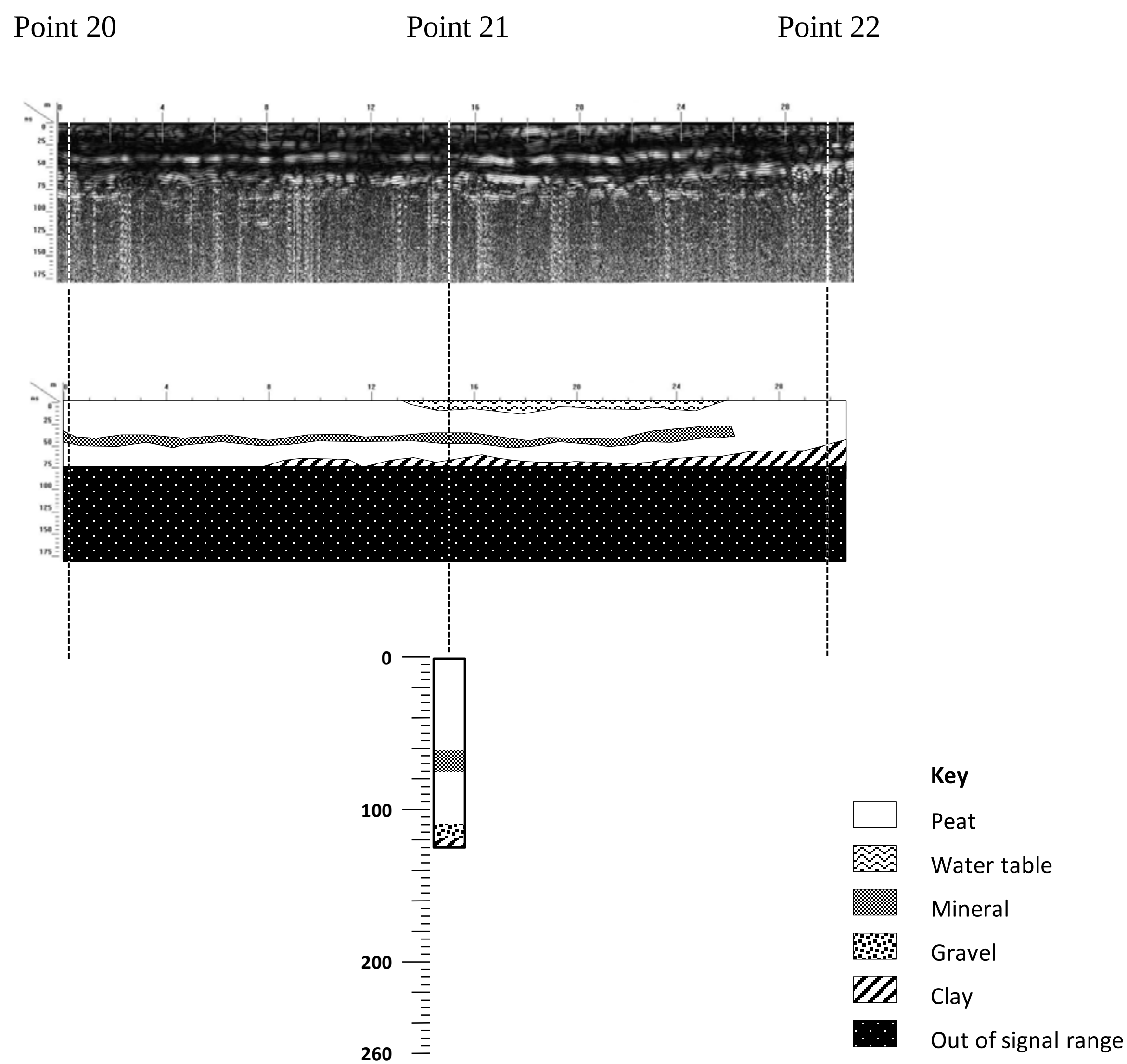

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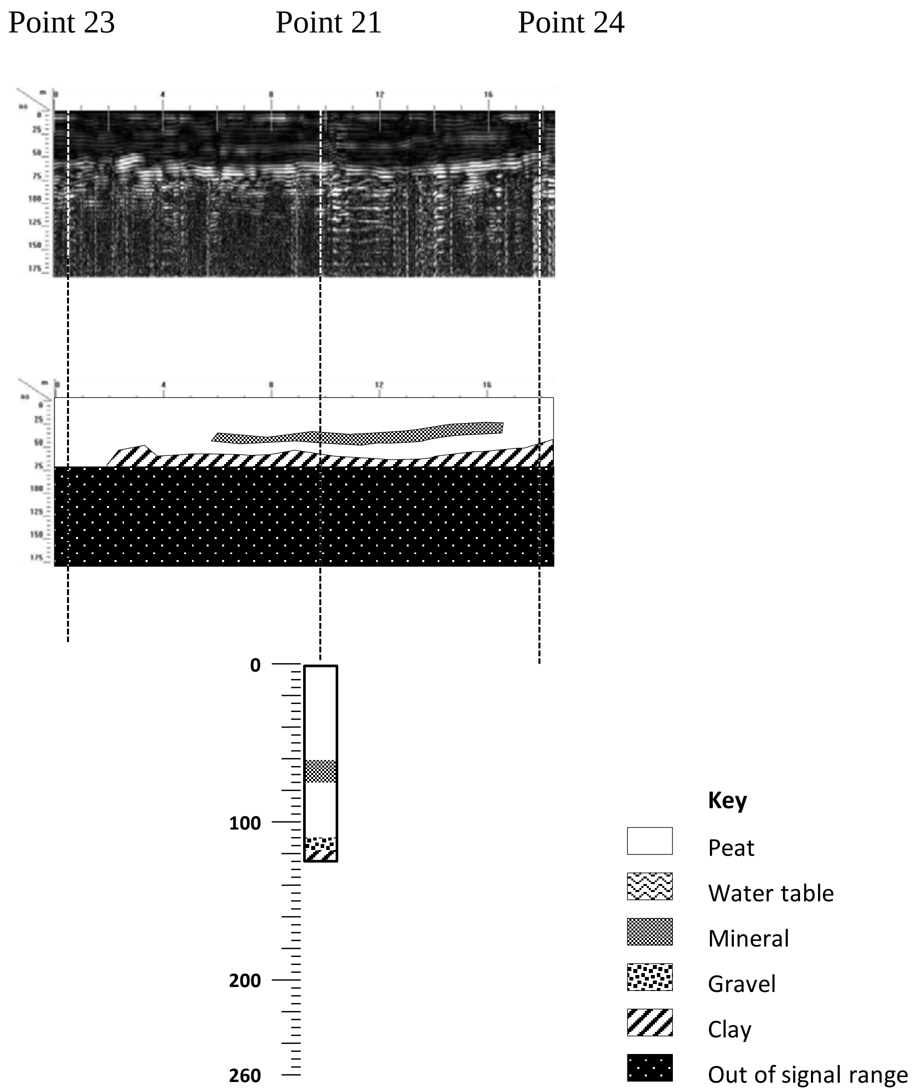

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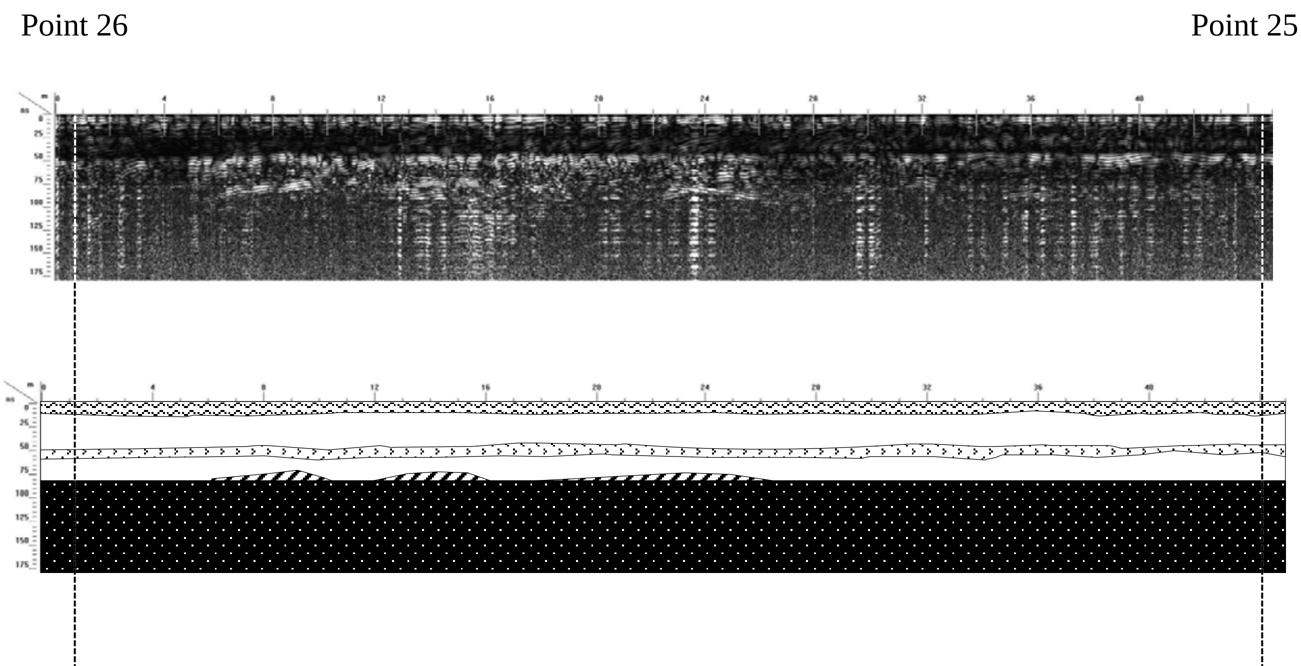
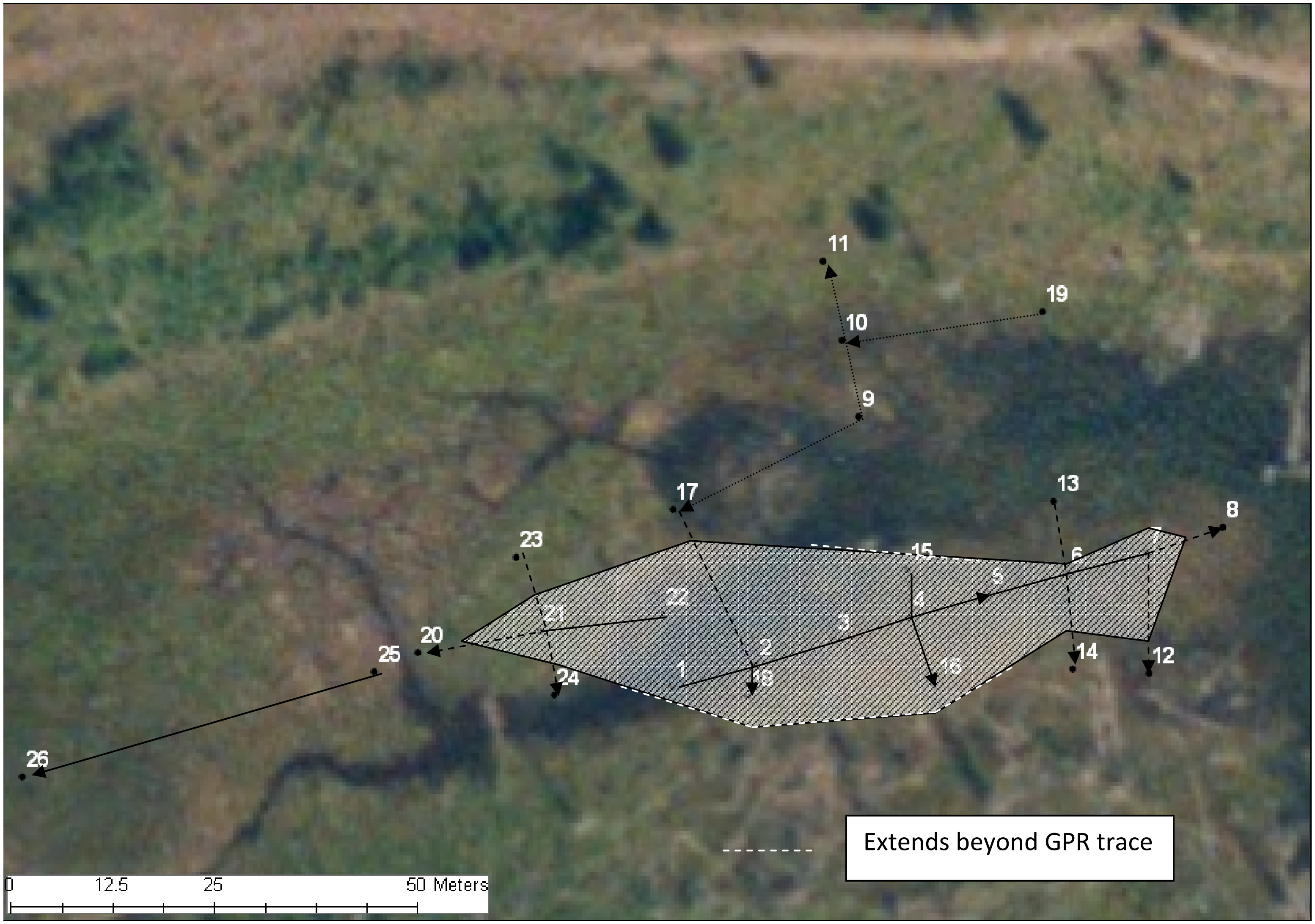


Key

- Peat
- Water table
- Assumed mineral
- Assumed clay
- Out of signal range

Site 209 - Estimated extent of continuous mineral layer



REFERENCES

Alberta Municipal Affairs (2013), Location and History Profile, www.municipalaffairs.alberta.ca/cfml/MunicipalProfiles/basicReport/HIST/0382.pdf, Accessed on 11th October 2013.

Barber, L. A. (2010), The origin of a mineral lens located in a Canadian Rocky Mountain peatland, Undergraduate thesis, department of Environmental Earth Sciences, University of Saskatchewan.

Belyea, L., Baird, A. (2006), Beyond "The Limits to Peat Bog Growth": Cross-scale feedback in peatland development, Ecological Monographs, 76 (3), 299-322.

Benistoun, M. (2003), Climatic change in mountain regions: A review of possible impacts, Advances in Global Change Research, 15, 5-31.

Berkes, F. (1998), Indigenous knowledge and resource management systems in the Canadian subarctic, Linking social and ecological sytems; Management practices and social mechanisms for building resilience, Chapter 5, Cambridge University press.

Beylea, L. R., Malmer, N. (2004), Carbon sequestration in peatland: patterns and mechanisms of response to climate change, Global Change Biology, 10, 1043-1052.

Bhat, M., G., Huffaker, R., G.,Lenhart, S., M. (1993), Controlling forest damage by dispersive beaver populations: Centralized optimal management strategy, Ecological Applications, 3 (3), 518-530.

Bhiry, N., Payett, S., Robert, E. (2007), Peatland development at the arctic tree line (Quebec Canada) influenced by flooding and permafrost,Quaternary Research, 67, 426-437.

Bigler, W., Butler, D. R. and Dixon, R. W. (2001), Beaver-pond sequence morphology and sedimentation in northwestern Montana, Physical Geography, 22(6), 531-540.
Bragg, O., M, (2002), Hydrology of peat forming wetlands in Scotland, The Science of the Total Environment, 294, 111-129.

Broder, T., Blodau, C., Biester, H., Knorr, K. (2012), Peat decomposition records in three pristine ombrotrophic bogs in southern Patagonia, Biogeosciences, 9, 1479-1491.

Butler, D. R. and Malanson, G. P. (1995), Sediment rates and patterns in beaver ponds in a mountain environment, Geomorphology 13, 255-269.

Butler, D. R. and Malanson, G. P. (2005), The geomorphic influences of beaver dams and failures of beaver dams, Geomorphology 71, 48– 60.

Chadde, S., Shelly, S., Bursik, R., Moseley, R., Evenden, A., Mantas, M., Rabe, F., Heidel, B. (1998), Peatlands on national forests of the northern Rocky Mountains: Ecology and conservation, US Forest Service, Rocky Mountain Research Station, General technical report RMRS-GTR-11, 75pgs.

Charman, D. (2002), Peatlands and environmental change, John Wiley & Sons Ltd., Chichester, England. ISBN 0-471-96990-7

Charman, D., West, S., Kelly, A. (1995), Environmental change and tephra deposition: the Strath of Kildonan, northern Scotland, Journal of Archaeological Science, 22, 799-809.

Chimner, R., Lemly, J., Cooper, D. (2010), Mountain fen distribution, types and restoration priorities, San Juan Mountains, Colorado, USA, Wetlands, 30, 763-771.

Chiverrell, R., Jakob, M. (2013), Radiocarbon dating: Alluvial fan/debris cone evolution and hazards, Dating torrential processes on fans and cones, *Advances in Global Change Research*, 47, 265-282.

Clymo, R. (1984), The limits to peat bog growth, Philosophical Transactions of the Royal Society of London, 303, 605-654.

Clymo, R. (2004), Hydraulic conductivity of peat at Ellergower Moss, Scotland, Hydrological Processes, 18, 261-274.

Cole, C., Brooks, R., Wardrop D. (1997), Wetland hydrology as a function of hydrogeomorphic (HGM) subclass, Wetlands, 17 (4), 456-467.

Conover, D. (2011), Keystone role of beavers in a restored wetland (Ohio), Ecological Restoration, 29 (3), 212-213.

Conover, M., R. (1994), Perceptions of grass-roots leaders of the agricultural community about wildlife damage on their farms and ranches, Wildlife Society Bulletin, 22 (1), 94-100.

Corenblit, D., Gurnell, A., Steiger, J., Tabacchi, E. (2008), Reciprocal adjustments between landforms and living organisms: Extended geomorphic evolutionary insights, Catena, 73, 261-273.

Crill, P. M., Bartlett, K. B., Harriss, R. C., Gorham, E., Verry, E. S., Sebacher, D. I., Madsar, L., Sanner, W. (1988), Methane flux from Minnesota peatlands, Global Biogeochemical Cycles, 2(4), 371-384.

Cunningham, J. M., Calhoun, A. J. K., and Glanz, W. E. (2006), Patterns of beaver colonization and wetland change in Acadia National Park, Northeastern Naturalist, 13(4): 583-596.

Davis, A. (1994), Ombrotrophic peatlands in Newfoundland Canada: Their origin, development and trans-atlantic affinities, Chemical Geology, 44, 287-309.

Devito, K. J. and Dillon, P. J. (1993), Importance of runoff and winter anoxia to the P and N dynamics of a beaver pond, Canadian Journal of Fisheries and Aquatic Science, 50, 2222–2234.

Engel, Z., Skyrzypek, G., Debajyoti, P., Drzewicki W., Nyvit, D. (2010), Sediment lithology and stable isotope composition of organic matter in a core from a cirque in the Krkonose Mountains, Czech Republic, Journal of Paleolimnology, 43, 609-624.

Ferguson, A., Osborn, G. (1981), Minimum age of deglaciation of upper Elk Valley, British Columbia, Canadian Journal of Earth Science, 18, 1635-1636.

Finlayson, C., Davidson, N., Spiers, A., Stevenson, N. (1999), Global wetland inventory – current status and future priorities, Marine an Freshwater research, 50 (8), 717-727.

Fisher, M (2013), Ground Penetrating Radar used to uncover the mysteries beneath our feet, Soil Horizons, 4 (6), Feature pgs 1-4.

Ford, T. E., Naiman, R. J. (1988), Alteration of carbon cycling by beaver: Methane evasion rates from boreal streams and rivers, Canadian Journal of Zoology, 66, 529-533.

Formann, R., Friedman, D. S., Fitzhenry, D., Martin, J., Chen, A., Alexander, L. (1997), Ecological effect of roads: Towards three summary indices and an overview for North America, Habitat fragmentation and infrastructure, Ministry of Transport, Public Works and Water Management, Delft, The Netherlands. 39-54.

Fournier, R., Grenier, M., Lavoie, A., Helie R. (2007), Towards a strategy to implement the Canadian wetland inventory using satellite remote sensing, Canadian Journal of Remote Sensing, 33 (S1), S1-S6.

Gorham, E., Lehman, C., Dyke, A., Janssens, J. and Dyke, L (2007), Temporal and spatial aspects of peatland initiation following deglaciation in North America, Quaternary Science Reviews 26, 300-311.

Greb, S., DiMichele, W., Gastaldo, R. (2006), Wetlands through time, Geological Society of America, Special Paper 399.

Gunther, K. A., M. J. Biel, and H. L. Robison (1998), Factors influencing the frequency of road-killed wildlife in Yellowstone National Park, Proceedings of the international conference on wildlife, the environment and transportation, Report No. FL-ER-69S58, Fort Myers, Florida, USA. 32–40.

Gurnell, A. M. (1998), The Hydrogeomorphological effects of beaver dam activity, Progress in Physical Geography, 22(2), 167-189.

Gustavson, K., Kennedy, E. (2010), Approaching wetland valuation in Canada, Wetlands, 30, 1065-1076.

Gvernment of Alberta, Maps and data summaries, June 19-22 strom event; http://www.environment.alberta.ca/forecasting/data/precipmaps/event_Jun19_22.PDF, accessed 15 October 2013.

H.A.P. Ingram (1983), Hydrology, A.J.P. Gore (Editor), Ecosystems of the World 4A, Mires: Swamp, Bog, Fen and Moor, Elsevier, Oxford, 67–158.

Halabisky, M., Hannam, Long, A. L., Vondrasek, C., Moskal, M. (2013), The sharper image: Hyperspatial remote sensing of wetlands, Wetland Science and Practice, 30 (2), 12-31.

Halley, D., Rosell, F., Saveljev, A. (2012), Population and distribution of Eurasian beaver (*Castor fiber*), Baltic Forestry, 18 (1), 168-175.

Hallworth, B., Chinnappa, C. (1997), Plants of Kananaskis Country In the Rock Mountains of Alberta, The University of Calgary Press, ISBN 0-88864-297-0.

Halsey, L., Vitt, D., Zoltai, S. (1997), Alberta wetland inventory standards, *In* Alberta vegetation inventory standards manual, version 2.2, *Compiled by* R. Nesby, Alberta Environmental Protection, Edmonton, Alberta.

Halsey, L., Vitt, D., Zoltai, S. (1997), Climatic and physiographic controls on wetland type in Manitoba, Canada, Wetlands, 17, 243-262.

Hebblewhite, M., White, C., Nietvelt, C., McKenzie, J., Hurd, T., Fryxell, J., Bayley, S., Paquet, P. (2005), Human activity mediates a trophic cascade caused by wolves, Ecology, 86 (8), 2135-2144.

Hey, D., Philippi, N. (1995), Flood reduction through wetland restoration: The upper Mississippi River basin as a case study, Restoration Ecology, 3 (1), 4-17.

Holden, J. (2009), Flow through macropores of different size classes in blanket peat, Journal of Hydrology, 364, 342-348.

Hood, G. A. and Bayley, S. E. (2008), Beaver (*Castor canadensis*) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada, Biological Conservation 141, 556-567.

Ise, T., Dunn, A., Wofsy, S., Moorcroft, P. (2008), High sensitivity of peat decomposition to climate change through water-table feedback, Nature Geoscience, 1, 763-766.

Ives, R. L. (1942), The beaver meadow complex, Journal of Geomorphology, 5, 191-203.

Janzen, K., Westbrook, C. (2011), Hyporheic flows along a channelled peatland: Influence of beaver dams, Canadian Water Resources Journal, 36 (4), 331-347.

Jarema, S., Samson, J., McGill, B., Murray, M. (2009), Variation in abundance across a species' range predicts climate change responses in the range interior will exceed those at the edge: a case study with North American beaver, Global Change Biology, 15, 508-522.

John, S., and Klein A. (2004), Hydrogeomorphic effects of beaver dams on floodplain morphology: avulsion processes and sediment fluxes in upland valley floors (Spessart, Germany), Quaternaire, 15(1-2), 219-231.

Johnston, C. (2001), Wetland soil landscape alteration by beavers, Wetland Soils: Genesis, Hydrology, Landscapes and Classification (editors – Verpraskas, M., Craft, C., Richardson, J.), Chapter 19, CRC Press, ISBN 1-56670-484-7.

Johnston, C., Naiman, R. (1990), Aquatic patch creation in relation to beaver population trends, Ecology, 71 (4), 1617-1621.

Johnston, C., Naiman, R. (1990), The use of a geographic information system to analyze long-term landscape alteration by beaver, Landscape Ecology, 4 (1), 5-19.

Jol, H. (1995), Ground penetrating radar antennae frequencies and transmitter powers compared for penetration depth, resolution and reflection continuity, Geophysical Prospecting, 43, 693-709.

Jol, H., Bristow, C. (2003), GPR in sediments: Advice on data collection, basic processing and interpretation, a good practice guide, Geological Society of London special publications, 211, 9-27.

Kramer, N., Wohl, E. E., Harry, D. L. (2012), Using ground penetrating radar to ‘unearth’ buried beaver dams, Geology, 40, 43-46.

Kuhry, P. (1994), The role of fire in the development of sphagnum-dominated peatlands in western boreal Canada, Journal of Ecology, 82, 899-910.

Kuhry, P., Turunen, J. (2006), The postglacial development of boreal and subarctic peatlands, *In* Boreal Peatland Ecosystems, *Edited by* Wieder, R. Vitt, D., Ecological Studies, 188, 26-46.

Lamentowicz, M., Van Der Knapp, W., Van Leeuwen,J., Hangartner, S., Mtchell, E., Goslar, T., Tinner, W., Kamenik, C. (2010), A multi-proxy high-resolution approach to reconstructing past environmental change from an Alpine peat archive, Page news (Peatlands: Paleoenvironments and Carbon Dynamics), 18 (1), 13-16.

Lang, M., McCarty, G. (2009), Lidar intensity for improved detection of inundation below the forest canopy, Wetlands, 29 (4), 1166-1178.

Loisel, j., Yu, Z., Parsekian, A., Nolan, J., Slater, L. (2013), Quantifying landscape morphology influence on peatland lateral expansion using ground penetrating radar (GPR) and peat core analysis, Journal of Geophysical Research, 118, 373-384.

Lowry, C., Fratta, D., Anderson, M. (2009), Ground penetrating radar and spring formation in a groundwater dominated peat wetland, Journal of Hydrology, 373, 68-79.

Luckman, B. (2000), The little ice age in the Canadian Rockies, Geomorphology, 32, 357-384.

MacDonald, G. (1981), Late Quaternary period paleoenvironments of the Morely Flats and Kananaskis Valley of southwestern Alberta, Canadian Journal of Earth Science, 19, 23-35.

Martell, K. A., Foote, A. L. and Cumming, S. G. (2006), Riparian disturbance due to beavers (Castor canadensis) in Alberta's boreal mixedwood forests: Implications for forest management, Ecoscience 13(2): 164-171.

Maxa, M., Bolstad, P. (2009), Mapping northern wetlands with high resolution satellite images and lidar, Wetlands, 29 (1), 248-260.

McKinstry, M., Caffrey, P., Anderson, S. (2001), The importance of beaver to wetland habitats and waterfowl in Wyoming, Journal of the American Water Resources Association, 37 (6), 1571-1577.

Mclain, M., Boyer, E., Dent, C., Gergel, S., Grimm, N., Groffman, P., Hart, S., Harvey, J., Johnston, C., Mayorga, E., McDowell, W., Pinay, G. (2003), Biogeochemical hotspots and hot moments at the interface of terrestrial and aquatic ecosystems, Ecosystems, 6, 301-312.

Mellet, J. S. (1995), Profiling of ponds and bogs using ground-penetrating radar, Journal of Paleolimnology 14, 233-240.

Messmer, T. (2000), The emergence of human-wildlife conflict: turning challenges into opportunities, International Biodeterioration and Biodegradation, 45, 97-102.

Milbrath, J. (2013), Land cover change within the peatlands along the Rocky Mountain Front, Montana: 1937-2009, MSc Thesis (Geography), University of Montana, Missoula, Montana.

Mitchell, C. C., and Niering, W. A. (1993), Vegetation change in a topogenic bog following beaver flooding, Bulletin of the Torrey Botanical Club, 120(2), 136-147.
Mitsch, W., Gosselink, J (1993), Wetlands 2nd Edition, Wiley.

Moore, K. (2012), Negotiating the middle ground in a world-system: The Niitsitapi (Blackfoot) and Ktunaxa (Kootenai) in the Northern Rocky Mountain Fur Trade, MSc Thesis, University of Arizona.

Naegeli, M. W., Huggenberger, P. and Uehlinger, U. (1996), Ground penetrating radar for assessing sediment structure in the hyporheic zone of a prealpine river, Journal of the North American Benthological Society, 15(3), 353-366.

Naiman, R. J, Johnston, C. A. and Kelley, J. C. (1988), Alteration of North American streams by beaver, Bioscience, 38(11), 753-762.

Naiman, R. J., Melillo, J. M. and Hobbie, J. E. (1986), Ecosystem alteration of boreal forest stream by beaver (*Castor canadensis*), Ecology, 67(5), 1254-1269.

Neal, A. (2003), Ground-penetrating radar and its use in sedimentology: principles, problems and progress, Earth Science Reviews, 66, 261-330.

Neff, D. (1957), Ecological effects of beaver habitat abandonment in the Colorado Rockies, The Journal of Wildlife Management, 21 (1), 80-84.

Nolet, B. A., Rosell, F. (1998), Comeback of the beaver *Castor fiber*: An overview of old and new conservation problems, Biological Conservation, 83(2), 165-173.

Oelhoeft, G. (2000), Maximising the information return from ground penetrating radar, Journal of Applied Geophysics, 43, 175-187.

Oetelaar, G., River of change: A model for the development of terraces along the Bow River, Alberta, Geographie Physique et Quaternaire, 56 (2-3), 155-169.

Pastor, J., Bonde, J., Johnston, C., Naiman, R. (1993), Markovian analysis of the spatially dependent dynamics of beaver ponds, Lectures on Mathematics in the Life Sciences, 23, 5-28.

Persico, L., Meyer, G. (2009), Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming, Quaternary Research, 71, 340-353.

Polvi, L., Wohl, E. (2012), The beaver meadow complex revisited – the role of beaver in post-glacial flood plain development, Earth Surface Processes and Landforms, 37, 332-346.

Polvi, L., Wohl, E. (2012), The beaver meadow complex revisited – the role of beavers in post-glacial flood plain development, Earth Surfaces Processes and Landforms, 37 (3), 332-346.

Pyne-O'Donnell, S., Hughes, P., Foese, D., Jensen, B., Keuhn, S., Mallon, G., Amesbury, M., Charman, D., Daley, T., Loader, N., Mauquoy, D., Street-Perrott, F., Woodman-Ralph, J. (2012), High-precision ultra-distal Holocene tephrochronoloy in North America, Quaternary Science Reviews, 52, 6-11.

Racine, C. H. and Walters, J. C. (1994), Groundwater-discharge fens in the Tanana lowlands, interior Alaska, U.S.A., Arctic and Alpine Research, 26(4), 418-426.

Ray, A. M., Rebertus, A. J. and Ray, H. L. (2001), Macrophyte succession in Minnesota beaver ponds, Canadian Journal of Botany, 79, 487-499.

Rebertus, A. J. (1986), Bogs as beaver habitat on north-central Minnesota, The American Midland Naturalist, 116(2), 240-245.

Reddoch, J., Reddoch, A. (2005), Consequences of beaver, *Castor Canadensis,* flooding on a small shore fen in southwestern Quebec, The Canadian Field Naturalist, 119, 385-394.

Reeve, A., Siegel, D., Glaser, P. (2000), Simulating vertical flow in large peatlands, Journal of Hydrology, 227, 207-217.

Roulet, N. (1990), The hydrological role of peat-covered wetlands. The Canadian Geographer, 34 (1), 82-83.

Roulet, N., Crill, P., Comer, N., Dove, A., Boubonniere R. (1997), CO_2 and CH_4 flux between a boreal beaver pond and the atmosphere, Journal of Geophysical Research, 102 (D24), 29,313-29,319.

Ruedemann R., Schoonmaker, W. J., (1938), Beaver-dams as geologic agents, Science 88(2292), 523–525.

Rydin, H. and Jeglum, J. (2006), The biology of peatlands, Oxford University press, Oxford.

Siegel, D. (1983), Ground water and the evolution of patterned mires, glacial Lake Aggasiz peatlands, Minnesota, Journal of Ecology, 71, 913-921.

Slater, L. D. and Reeve, A. (2002), Investigating peatland stratigraphy and hydrogeology using integrated electrical geophysics, Geophysics, 67(2), 365-378.

Soil Classification Working Group (1998), The Canadaian System of Soil Classification, 3rd Edition, Agriculture and Agri-Food Canada Publication 1646, 187pp. ISBN 0-660-17404-9.

Squeo, F., Warner, B., Aravena, R., Espinoza, D. (2006), Bofedales: High altitude peatlands of the central Andes, Revista Chilena de Historia natural, 79, 245-255.

Stein, E., Mattson, M., Fetscher, A., E., Halama, K. (2004), Influence of geologic setting of slope wetland hydrodynamics, Wetlands, 24 (2), 244-260.

Stevens, C., Paszkowski, C., Scrimigeour, G. (2006), Older is better: Beaver ponds on boreal streams as breeding habitat for the wood frog, Journal of Wildlife Management, 70 (5), 1360, 1371.

Strack, M., Kellner, E., Waddington, J. (2005), Dynamics of biogenic gas bubbles in peat and their effects on peatland biogeochemistry, Global Biogeochemical Cycles, 19, 1-9.

Strack, M., Waddington, J., Rochefort, L., Tuittila, E. (2006), Response of vegetation and net ecosystem carbon dioxide exchange at different peatland microforms following water table drawdown, Journal of Geophysical Research: Biogeosciences, 111 (G2), 1-10.

Tardif, S., St-Hilaire, A., Roy, R., Bernier, M., Payette, S. (2009), Statistical properties of hydrographs in minerotrophic fens and small lakes in mid-latitude Quebec, Canada, Canadian Water Resources Journal, 34 (4), 365-380.

Terwilliger, J. and Pastor, J. (1999), Small mammals, ectomycorrhizae, and conifer succession in beaver meadows, OIKOS 85, 83-94.

Tiit Hang, S., Wastegard, S., Heinsalu, A., Heinsalu, V. (2006), First discovery of crypto tephra in Holocene peat deposits of Estonia, eastern Baltic, Boreas, 35, 644-649.

Tornblom, J., Angelstam, P., Hartman, G., Henrikson, L., Sjoberg, G. (2011), Toward a research agenda for water policy implementation: Knowledge about beaver (*Castor fiber*) as a tool for water management with a catchment perspective, Baltic Forestry, 17 (1), 154-161.

Turetsky, M., St. Louis, V. (2006), Disturbance in boreal peatlands, Ecological Studies Volume 188, 359-379.

United Nations Environment Program (UNEP) http://maps.grida.no/go/graphic/peat-distribution-in-the-world Last accessed 12/2/2011.

Vance, R., Beaudoin, B., Luckman, B. (1995), The paleoecological record of 6 ka BP climate in the Canadian Prairie Provinces, Geographie physique et Quaternaire, 49 (1), 81-98.

Vitt, D., Haley, L., Thormann, M., Martin, R. (1996), Peatland inventory of Alberta, Alberta Peat Task Force, Network of Centres of Excellence in Sustainable Forest Management Grant, University of Alberta, Edmonton, Alberta.

Waddington, J., Roulet., N. (2000), Carbon balance of a boreal patterned peatland, Global Change Biology, 6, 87-97.

Walbridge, M. (1994), Plant community composition and surface water chemistry of fen peatlands in West Virginia’s Appalachian plateau, Water, Air and Soil Pollution, 77, 247-269.

Warner, B. G., (2005), Canadian Peatlands, http://www.landesmuseum.at/pdf_frei_remote/STAPFIA_0085_0353-0372.pdf accessed on 09/22/2011.

Westbrook C., Cooper D., Butler D. (2013), Beaver geomorphology and hydrology. In: Treatise on Geomorphology – Ecogeomorphology (Butler D, Hupp C, eds.), Elsevier, chapter 23, 293-306.

Westbrook, C. J., Cooper, D. J., and B. W. Baker (2006), Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area, Water Resources Research, 42, W06404, doi:10.1029/2005WR004560.

Westbrook, C. J., Cooper, D. J., Baker, B. W. (2011), Beaver Assisted River Valley Formation, River Research and Applications, 27, 247–256.

Whitfield, C., Baulch, H., Chun, K., Westbrook, C. (2013), Population growth makes beaver important agents of global CH4 emissions, submitted to; Global Biogeochemical Cycles.

Whittington, P., Price, J. (2006), The effects of water table draw down-down (as a surrogate for climate change) on the hydrology of a fen peatlands, Canada, Hydrological Processes, 20 (17), 3589-3600.

Wilson, S., Griffiths, M., Anielski, M. (2009), The Alberta GPI accounts – wetlands and peatlands, The Pembina Institute for Appropriate Development, ISBN 0-921719-68-X.

Wolff, E., Cooper, D., Hobbs, N. (2007), Hydrologic regime and herbivory stabilize an alternative state in Yellowstone National Park, Ecological Applications, 17 (6), 1572-1587.

Wright, J., Flecker, A., Jones, C. (2003), Local vs. landscape controls on plant species richness in beaver meadows, Ecology, 84 (12), 3162-3173.

Yavitt, J., Lang, G., Sexstone, A. (1990), Methane fluxes in wetland and forest soils, beaver ponds and low-order streams of a temperate forest ecosystem, Journal of Geophysical Research, 95 (D13), 22,463-22,474.

Zoltai, S, Siltanen, R., Johnson, J. (2000), A wetland database for the western boreal, subarctic and arctic regions of Canada. Natural Resources Canada, Northern Forestry Centre, Information report NOR-X-368.

Zoltai, S. (1989), Late Quaternary volcanic ash in the peatlands of central Alberta, Canadian Journal of Earth Science, 26, 207-214.

Zoltai, S. C., Vitt, D. H. (1995), Canadian wetlands: Environmental gradients and classification, Vegetation, 118, 131-137.