1 **Properties and Processes of Recently Established Soils from Deglaciation of Cierva Point,**
2 **Western Antarctic Peninsula**

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10 **ABSTRACT**

11 For more than sixty years the Antarctic Peninsula has experienced significant temperature
12 increases that have accelerated glacial retreat. Glacial losses, along with the relatively warm and
13 moist climatic conditions of the region, have increased the rate of soil development. The
14 objective of this study is to study the properties and genesis, of soils at Cierva Point, which is
15 located in the zone of maximum warming along the western Antarctic Peninsula. Cierva Point is
16 a terraced, steeply sloping, ice-free peninsula containing a small retreating glacier. The
17 peninsula contains a large penguin rookery and significant areas of moss buildup. Twenty-seven
18 soils were described and physical and chemical properties from each horizon were analyzed.
19 Four categories of soil were identified: acidic (pH < 5), neutral (pH > 5), moss-dominated (high
20 organic matter accumulations), and ornithogenic (high phosphorus accumulations). Neutral soils
21 were newly formed soils which had undergone the least development and were located closest to
22 the glacier margin. Acidic soils were located farthest from the glacier margin, allowing for a
23 greater nutrient leaching to occur; these soils have extremely low pH values (as low as 3.5) but
24 did not have the high phosphorus accumulations found in ornithogenic soils or the high soil

25 carbon content found in moss-dominated soils. In a region with rapidly retreating glaciers, such
26 as the Antarctic Peninsula, proximity to the glacier margin becomes an important factor
27 determining soil properties. Soils farther from the glacier have had more time to be affected by
28 leaching, penguin activity, and moss buildup.

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30 *Key words:* Soil classification, Antarctic Peninsula, Ornithogenic soils, Soil acidity

1. INTRODUCTION

Since the 1950's air temperature along the Western Antarctic Peninsula (WAP) has risen at a rate of 0.56°C per decade (Turner *et al.*, 2005). These temperature increases have led to rapid glacial retreat and subsequent land exposure. The newly exposed ice-free regions are subjected to physical and chemical weathering processes which contribute to the development of soils throughout the WAP. Relatively warm summer temperatures and moist climatic conditions that are common along the peninsula enhance biologic and chemical processes, which increase the rates of mineral transformation and translocation of materials (Blume *et al.*, 2004).

Research on soil forming factors on the WAP and their relative influence on soil development is currently in its inception stage, with many studies focusing on regions having experienced no previous soil investigations (Jeong *et al.*, 2004; Lee *et al.*, 2004; Navas *et al.*, 2008; Simas *et al.*, 2008; Francelino *et al.*, 2011; Moura *et al.*, 2012; Souza *et al.*, 2014). With the large presence of abundant penguin rookeries throughout the WAP, there has been an emphasis on 'ornithogenic soils,' or soils that are significantly affected by avian activity (Tatur, 1989; Blume *et al.*, 2004; Michel *et al.*, 2006; Simas *et al.*, 2007; Moura *et al.*, 2012; Mendonça *et al.*, 2013; Souza *et al.*, 2014). These studies are very comprehensive and have reported that guano from nesting penguins not only contributes nutrients such as phosphorus but also significantly acidifies soils within and adjacent to nesting areas. Another point of research interest along the WAP has been on the effect of moss presence on soil properties; these studies have found that moss growth significantly increases soil carbon and increases acidity through organic acid release (Beyer *et al.*, 1999; Bolter, 2011). However, the moss cover in many of these studies has been thin or intermittent, making it difficult to assign soil properties directly to the presence of moss beds. Although most present day soils on the WAP are developing in

proximity to retreating glaciers, few studies have focused on how physical or chemical soil properties change with distance from the glacial margin (Strauss *et al.*, 2009).

The objective of this study was to analyze the physical and chemical properties of the soils throughout Cierva Point, assess the key soil-forming factors and processes.

2. SITE DESCRIPTION

Cierva Point (64.15°S, 60.95°W) is a small, ice-free peninsula (1 km north to south and 1.5 km east to west) pointing to the north-northwest; the peninsula is protected from local climatic extremes by the larger Vivot Point and Mt. Pepino on opposite (northern) side of the cove (Fig. 1). Brabant Island, located to the west, protects the Cierva coastline from the effects of the open ocean. The climate is cold marine, with a mean annual air temperature of approximately -3.2°C and annual precipitation ranging between 400 and 1,100 mm. Winter snow depths could exceed 1 m; however, during the summer most of the seasonal snow completely melts. The study area generally slopes to the north exposing it to high solar radiation inputs during the summer. Ground temperatures throughout the peninsula were high enough that permafrost could not be detected within 2 m of the ground surface, and a borehole at the site suggests that it currently might be 6 m or more below the surface (Bockheim *et al.*, 2013).

Bedrock of Cierva Point is of intrusive igneous origin. The northernmost lowlands consist of granodiorites with very large dolerite xenoliths (>1 m). The middle of the peninsula (uphill and to the south) is dominated by crystallized orthoclase feldspar granites. Both granitoid regions contain dikes composed of dolerite. The contact region between the granodiorite and granite shows signs of contact metamorphism. The eastern side of the peninsula, along with the southern peaks, is dominated by basalts containing olivine and quartz crystals.

Polished bedrock, striations, and chatter marks on bedrock throughout the peninsula indicate that, at one time, nearly the entire region was glaciated. Based on the current glacier position, it is likely that the entire slope was glaciated as recently as a couple hundred years ago. The one exception to this was at the highest elevation of this study (301 m above sea level) where there were no signs of glaciation on the ridgetops. Currently, a majority of the peninsula is ice-free; however, the eastern portion is dominated by a large, but quickly retreating glacier. The terrain of Cierva Point is steep, punctuated by several natural terraces. Slopes vary from 0 to 20% on benches and 30 to 60% on bedrock cliffs. Terraces contain several permanent ponds and unconsolidated materials with soils derived from weathered bedrock. These terraces are occupied for much of the year by Gentoo penguins (*Pygoscelis papua*) (ASPA No. 134, 2006).

Soils on penguin occupied benches are considered ornithogenic (Michel *et al.*, 2006), due to the large number of nesting sites found in the region. Features of ornithogenic soils include high accumulations of P and Ca and extreme acidity (Moura *et al.*, 2012). Typically, ornithogenic soils occur in regions where penguins can nest and have easy access to food, such as low-elevation sites that are far enough inland that guano deposits are not easily washed away (Tatur, 1989). The lowest elevations of Cierva Point are occupied by penguin activity, as would be expected; however, nesting sites at elevations up to 280 m a.s.l. have been noted.

The northern (lowest elevation) region of Cierva Point is covered by significant moss (*Polytrichum strictum* and *Chorisodontium aciphyllum*) accumulations. Moss on Cierva Point is ubiquitous and unusually thick (up to 0.8 m deep). Other studies report moss buildup along the Antarctic Peninsula of less than 0.1 m thick (Guglielmin *et al.*, 2008).

3. MATERIALS AND METHODS

Twenty-seven pedons were described and classified from Cierva Point (Soil Survey Staff, 2014a). Soils were sampled to best represent the many geomorphic, topographic, and organic features found on Cierva Point (Tables 1 and 2). Areas affected by moss buildup were identified by O horizons and significant accumulations of soil organic carbon (SOC) (Bolter, 2011). Ornithogenic soils were selected based on observation of penguin activity and confirmed from phosphorus and calcium accumulations in the soils (Tatur, 1989). The soils were examined by hand-dug pits and described according to the *Field Book for Describing and Sampling Soils* (Schoenenberger *et al.*, 2012). The symbol “D” was used to describe surface stone layers.

Soil samples were air-dried and sieved to 2 mm prior to physical and chemical analyses using procedures of the Natural Resources Conservation Service (Soil Survey Staff, 2014b). Textures were determined using the hydrometer method. Soil pH was performed on a 1:1 soil to distilled water solution and a 1:2 soil to 0.01M CaCl₂ solution; and electrical conductivity from a 1:2 soil to distilled water solution (Pansu and Gautheyrou, 2007). Based on testing with dilute 1M HCL acid, carbonates are considered to be absent from the soils of Cierva Point. C and N were tested by combustion on a Flash EA 1112 16 CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy). Soils with a non-effervescent reaction class were assumed to have no inorganic C, with total C approximately equal to organic C. Extractable P, K, Ca, Mg, Fe, Al, and Na were determined by microwave digestion with HCl and H₂SO₄ and detection by ICP-OES (Maguire and Heckendorn, 2011). Free Fe-oxides were determined by dithionite-citrate extraction according to the method of Holmgren (1967) with detection by ICP-OES.

4. RESULTS

4.1. Soil properties

Twenty-three out of twenty-seven of the soils were described as either Entisols or Inceptisols due to the lack of or minimal diagnostic horizons and poor soil development (Table 2). Organic buildup at four sites was significant enough (10 cm for Folists and >40 cm for Sapristis) to designate them as Histosols. Average annual air temperatures at Cierva Point are below 0°C; however, no permafrost was found within 2 m of the ground surface, precluding the soils from being classified as Gelisols. Although no permafrost was detected at any of the sites, average annual air temperatures were low enough (below 8°C) for cryic modifiers, which are reflected in the soil suborder or great group designations (Soil Survey Staff, 2014a).

Soil depths ranged from 0.17 m (CP04) to over 1 m (CP02); depths typically varied depending on local geologic features such as bedrock ridges or depressions. Till accumulation and rock striations indicated that at one point most of the peninsula was glaciated. Moraines and the retreating glacier show that the eastern side of the peninsula was relatively recently deglaciated (dates unknown). Six soils (CP1-4, CP20, CP25) contained cryoturbation features and occurred on patterned ground features, including solifluction lobes, mud boils, and non-sorted polygons.

Based on physical, chemical, and geographic characteristics, soils were categorized into four groups: acidic, neutral, moss-dominated, and ornithogenic (Fig. 3). In this study acidic soils were defined as soils with average profile pH values under 5.0, while neutral soils were defined as soils with average profile pH values of greater than 5.0 (Fig. 4). To be considered an acidic or neutral soil, there could not be organic matter accumulations greater than 5 cm or average soil profile phosphorus accumulations over 8,000 mg/kg (this number was the average of all soil profiles). Soils with organic matter accumulations greater than 5 cm were categorized as moss-dominated, and soils with average profile accumulations of phosphorus greater than 8,000 mg/kg

were categorized as ornithogenic soils (Tables 3 and 4; Figs. 5, 6). These properties were chosen as the definition of each category because they were the distinguishing characteristics for all soils in the study area.

4.2. Acidic Soils

This is the dominant soil group of Cierva Point and is represented by CP04, CP06, CP10, CP17, CP18, and CP19. These soils were most commonly found in the northern and western portions of the peninsula where moss or penguin contributions were less frequent. Acidic soils of Cierva Point were characterized by pH values below 5.0 (Table 4). Soil textures were generally sand to sandy loam and the soils are all light to dark brown (2.5Y 5/2 - 10YR 3/3) in color. Only CP04, which was composed of nearly 25% clay, was identified as a sandy clay loam (Table 3). Four of the six acidic soils (CP04, CP10, CP18, CP19) had a Bw horizon but only in CP10 was the horizon strongly enough developed to be classified as a cambic horizon. One pedon (CP19) has an E horizon, indicating that some leaching was occurring (Fig. 3). The acidic soils tended to be well drained. However, gleying in the C horizon of CP17 could indicate a seasonally fluctuating water table.

Most of the acidic soils had organic matter and C buildups; however, they were not significant enough to be designated as Histosols. The C accumulations were most pronounced at the surface and decreased with depth (Table 4). Acidic soils had Na and electrical conductivity values that decreased with profile depth. All other elements examined in the acidic soils (C, P, K, Ca, Mg, Fe, Al) were neither relatively enriched nor depleted when compared to the other soils of Cierva Point. One exception to this was in CP04, which had significant depletions of P and K

when compared to the other acidic soils; CP04 also had much higher accumulations of C, Fe and Na than other acidic soils at Cierva Point.

4.3. Neutral Soils

Neutral soils include pedons CP01, CP02, CP03, and CP08. These soils were most commonly found on the east side of the peninsula in regions where moss or penguin contributions were minimal. Neutral soils of Cierva Point were characterized by having pH values between 5.0 and 8.0. Soil textures ranged from sands to sandy loam and were grey to dark brown (5Y 5/1 – 7.5YR 3/4) in color (Table 3). Two of the four neutral soils (CP01, CP03) had a Bw horizon, but only the Bw of CP01 qualified as a cambic horizon (Fig. 3). The two remaining pedons (CP02, CP08) had no identifiable A or B horizons. The neutral soils also did not have significant accumulations of water within the profile indicating good drainage. However, gleying in the C horizon of CP08 could indicate a seasonally fluctuating water table.

Neutral soils had no significant organic matter buildup, and C accumulations were very low compared to other soils at Cierva Point (Table 4). P accumulations in the neutral soils half those of other soils of Cierva Point. All other elements examined in the neutral soils (K, Ca, Mg, Fe, Al, Na) were neither relatively enriched nor depleted when compared to the other soils of Cierva Point.

4.4. Moss Soils

Soils significantly affected by the presence of moss beds included CP05, CP07, CP09, CP16, CP21, CP23, CP25, and CP27. These soils were characterized by thick moss buildup (up to 0.5 m thick). Moss-dominated soils were found in low-elevation (between 40 and 90 m a.s.l.)

bedrock depressions (such as CP09, CP21), on slopes (CP07, CP16, CP23, CP27), and on high-elevation ridges (CP05, CP25) (Fig. 3). Three of the moss-dominated soils had high enough soil organic matter buildups to be designated as Histosols, while the five remaining soils were identified as Inceptisols (Table 2). Moss-dominated soils were dark brown to red (7.5YR 3/2 – 10R 3/3) and are typically darker than other soils at Cierva Point. Soil texture in these soils ranged from sands to sandy loams (Table 3).

Most moss-dominated soils are acidic with pH values between 3.4 and 5.4; however, soils CP07 and CP09 had slightly more neutral pH values, between 5.3 and 6.2 (Table 4). C accumulations in these soils were markedly higher than other soils of Cierva Point, reaching more than 300 g/kg_{soil}, these C accumulations were highest near the ground surface but continued to be elevated at deeper depths within the soil profiles. Moss-dominated soils also had noticeable depletions of K, which were typically half that of other soils at Cierva Point. The two moss-dominated soils with more neutral pH values (CP07 and CP09) also had Mg, Fe, and Al accumulations which were significantly higher than any other moss dominated-soils; these values were more similar to accumulations measured in neutral moss-free soils. All other elements examined in the neutral soils (P, Ca, Na) were neither relatively enriched nor depleted when compared to the other soils of Cierva Point.

4.5. Ornithogenic Soils

Ornithogenic soils were most common on the northern and western sides of the peninsula, typically at the lower elevations; however, penguin nests were observed at much higher elevations. Soils identified as ornithogenic included CP11, CP12, CP13, CP14, CP20, and CP26. Five out of the six ornithogenic soils were identified as Entisols, while the sixth was an

Inceptisol. Soil textures ranged from sands to sandy loams, while colors were generally lighter than other Cierva Point soils, ranging from grey to dark brown (10YR 5/1 – 7.5YR 3/4) (Table 3). Four of the six ornithogenic soils (CP11, CP12, CP14, CP26) have Bw horizons (Fig. 3) and one (CP12) had an E horizon, indicating that leaching was occurring. Gleying in the C horizons of CP11 and CP20 indicate seasonally fluctuating water tables.

One of the most distinguishing chemical features of ornithogenic soils was the extremely high accumulations of P and Ca throughout the soil profile (Table 4). P accumulations in ornithogenic soils were nearly quadruple that of the highest non-ornithogenic soil (CP23). Ca accumulations in ornithogenic soils were also double that of the highest non-ornithogenic soil (CP09). One exception to the extreme accumulation of Ca was in CP20, which had accumulations equivalent to non-ornithogenic soils. The pH of ornithogenic soils were generally acidic, with values ranging from 3.3 to 6.3. Typically, only the surface horizons contained higher pH values; horizons below the ground surface all had pH values below 5.2. All other elements (potassium, magnesium, iron, aluminum, sodium, carbon) examined in the ornithogenic soils were neither relatively enriched nor depleted when compared to the other soils of Cierva Point.

5. DISCUSSION

5.1. Soil Forming Factors and Processes

Unlike most of the Antarctic Peninsula (Vieira *et al.*, 2010; Bockheim *et al.*, 2013), permafrost was not detected within 2 m of the ground surface at Cierva Point, indicating that the climatic environment of the small peninsula is unusually warm. As far north as Livingston Island (170

km north of Cierva Point) permafrost tables were detected in weathered materials at between 0.8 and 3.0 m below ground surface (Hauck *et al.*, 2007).

The lack of significant soil development and diagnostic horizons, coupled with the proximity of a retreating glacier, indicate that the bedrock of Cierva Point has recently been exposed and soil development has occurred for only a short time, on the order of a few centuries. There were no distinguishable differences in soil texture among the examined soils (Table 3); however, CP04, which was potentially never glaciated, had significant clay accumulations indicating a longer period of soil development. Increasing accumulations of clay in polar soils are indicative of longer periods of soil development (Navas *et al.*, 2005). There are two parent material sources for the development of soils at Cierva Point: glacier transport of till and bedrock breakdown into residuum. During glacial retreat large amounts of till were deposited throughout Cierva Point primarily as fine materials in-filling bedrock depressions and lateral moraines containing boulders as large as 2 m across. After glacial retreat from Cierva Point the exposed granitic and basaltic bedrock weathered, primarily through mechanical weathering through the freeze-thaw process; however, the presence of water and relatively warm temperatures are also conducive to chemical weathering of the soils. Chemical weathering is apparent from the leaching and accumulation of clay and nutrients in many of the soil profiles (Tables 3 and 4).

As indicated in Fig. 1, the relief of Cierva Point as a peninsula is very steep, rising 330 m in just under 2 km (16.5% slope averaged). However, the peninsula is punctuated by several nivation terraces which were nearly horizontal, to the point that they were able to retain large seasonal ponds (Table 1). It is on these terraces that many of the soil profiles exceeded 1 m in depth (Table 2). At mid-elevation locations the steeper slopes were occupied by moss buildup while the terraces were often occupied by penguins. At lower elevations the presence of

penguins was nearly ubiquitous while deep mosses were confined to bedrock depressions. There was little to no evidence of any significant eolian or volcanic accumulations in any of the soils of Cierva Point.

5.2. Mineral Soils Minimally Affected by Mosses and Penguins

Most non-ornithogenic and non-moss dominated soils examined at Cierva Point were slightly acidic to very acidic (as low as pH value 3.3) (Fig. 4). It is unlikely that the extremely low pH values were derived from parent material since no sulfidic deposits were found in the surrounding bedrock or till. The soils on Cierva Point are derived from granites and basalts, which typically are associated with neutral to basic pH soils (Moura *et al.*, 2012). Additionally, these soils did not exhibit sulfidic horizons, were not significantly yellowed, and contained no secondary sulfides, as were described in other acidified soils in the Antarctic (Simas *et al.*, 2008). With one exception (CP04), all of the acidic sites were located at low elevations in the northern half of the peninsula. Neutral pH locations, on the other hand, were located at mid-elevations and were in proximity to the retreating glacier (Fig. 2).

The low elevation, acidic soils were all located within or near a very large penguin rookery (Fig. 2) (ASPA No. 134, 2006). While not showing any signs of heavy penguin occupation, these sites were likely to have been lightly used or were relict rookeries. Nearby nesting sites and penguin activities contribute to the acidification of the unoccupied regions through the mineralization of nitric and sulfuric acids released from penguin guano (Bolter *et al.*, 1997). Other studies of soils in proximity to ornithogenic activities refer to these acidified soils as ‘weakly ornithogenic’ soils (Tatur, 1989; Michel *et al.*, 2006; Simas *et al.*, 2007; Moura *et al.*, 2012). While not as strongly evident as in strongly ornithogenic soils, cation accumulations at

the surface of the acidic soils indicate that there is significant biological activity immobilizing the cations. Analysis of relative phosphorus accumulations on non-ornithogenic acidified sites demonstrated that the acidified sites had phosphorus accumulations which were significantly lower than that of ornithogenic soils (Table 4). While lower than ornithogenic sites, the phosphorus accumulations in acidified soils were still double that of neutral sites, confirming that the acidification of these soils was from relict penguin occupation or were indirectly influenced by nearby occupied sites.

There was a clear geographic and temporal delineation in the locations of the acidic and neutral soils. The proximity of neutral soils to the retreating glacier (Fig. 2) indicates that newly deposited soils are not inherently acidic. Soils located farther from the glacial margin have had more time for acidifying materials (such as organic acids) to be deposited and leaching to occur. There is one exception to the geographic distribution of these soils; CP04, a highly acidic soil located in a bedrock depression at the highest elevation at Cierva Point which was almost completely surrounded by a glacier (Fig. 5). No vegetation was growing near this outcrop and, due to several vertical walls penguin activity was nonexistent. Given that soils near to the glacier margin are less acidified, CP04 should have a neutral pH, instead of the acidic values that were measured. However, there is no evidence (such as till or glacial scarring of the surrounding bedrock) of a glacier overriding this high elevation location, suggesting that CP04 is in an unglaciated ridge. The soils of CP04 are much older than other soils of equal distance from the glacier since their development was not dependent on the glacier retreating. The longer exposure of these soils allowed for greater accumulation of clays through weathering, along with the leaching of cations such as calcium and magnesium down the profile (Table 4). Beyer *et al.*

(1999) and Strauss *et al.* (2009) also report clay accumulation and leaching of base cations in soils along the WAP.

5.3. Moss-Dominated Soils

On Cierva Point, soils significantly influenced by moss growth were designated as moss-dominated soils. These soils were defined by significant O horizon buildups (Table 3) and high accumulations of soil organic carbon (Fig. 6). In their review on Antarctic soils, Beyer *et al.* (1999), reported that moss covers created carbon enriched soil horizons which had accumulations of carbon even at deeper depths due to cold temperatures retarding SOM breakdown. Geographically, moss-dominated soils were most prominent at low elevations in bedrock depressions; however, moss buildup was so significant at Cierva Point that moss beds greater than 0.1 m thick were growing on steep slopes and some mosses as thick as 0.1 m were found at 188 m a.s.l. (Table 1). Moss-dominated soils were interspersed with ornithogenic and acidic soils at mid and low-elevation sites. Two exceptions were CP07 and CP09, which were located near the glacier margin, close to several neutral pH soils (Fig. 2).

The effect of these significant moss buildups was most apparent in the accumulation of soil organic carbon in all moss-dominated soils. Average carbon buildups in the surface horizons of moss-dominated soils were triple that of neighboring non-moss-dominated acidic soils; however, carbon accumulations in the lower mineral horizons in the moss-dominated soils decreased to amounts equivalent to those measured on acidic soils (Table 4). Soil development was also influenced by the presence of surface organic mats (Table 3). These mosses would release organic acids that help chelate nutrients, such as iron, and transport them through the soil profile (Boxma, 1981). The transportation of some nutrients was so great that it would be

visually detected in the soil profiles, as all the moss-dominated soils had darker colors and were even red in some cases (Table 3). One location (CP16) had distinct podzolization occurring in the form of a Bs horizon. In the mineral horizons of most of the moss-dominated soils, both iron and aluminum accumulations increased with depth; whereas, in non-moss dominated soils, iron and aluminum accumulations typically remained stable with profile depth (Table 4).

On Cierva Point, soils are acidified by organic acids released by two sources: nitric acids released through ornithogenic activity (which will be discussed in the next section) and humic and fulvic acids released by moss (Bolter, 2011). In both bare and moss soils, pH values are extremely low, making it difficult to separate the acidifying contributions from both deposition processes; however, since pH values under moss beds are much lower than what has been found under other Antarctic moss beds (Wynn-Williams, 1985) it can be reasonably assumed that much of the acidification occurred prior to moss development. An exception to soil acidification on Cierva Point was in moss-dominated soils which developed near to the glacial margin. These soils were exposed or created relatively recently through glacial retreat and have had relatively little time to acidify. In these locations pH values are nearly neutral, similar to nearby bare soils. The neutral pH under these mosses implies that the moss beds grew prior to the acidification of the soils, as what happened to the acidic, moss-dominated soils farther from the glacial margin. The accelerated moss growth at Cierva Point is likely due to climatic conditions changing to be more conducive for faster moss growth. In polar regions, such as Cierva Point, moss growth is slow due to cold air temperatures and limited solar radiation; however, air temperatures along the Antarctic Peninsula have been shown to be consistently rising since the 1950's (Vaughan *et al.*, 2003), giving moss a greater chance to grow during the summer. Royles *et al.* (2013) found that, along the Antarctic Peninsula, moss accumulation rates increased from 1.5 mm/yr during the

early 20th century to over 5.0 mm/yr in the 1970's. They concluded that the increasing moss accumulation rates in recent decades were closely related to the rising air temperatures in the region.

5.4. Ornithogenic Soils

At the surface of ornithogenic soils, guano from nesting penguins contains large amounts of carbon, nitrogen, calcium, and phosphorus which dominate the soil (Fig. 7). Ammonium and calcium cations released during mineralization of the guano create high surface pH values, when compared to lower horizons (Mataloni *et al.*, 2010). The presence and effect of calcium cations at the soil surface at Cierva Point can be observed in Table 4 where the surface horizons of four out of the six ornithogenic soils had elevated accumulations of calcium and all six ornithogenic soils had high pH values at the soil surface. Mineralization of decomposed penguin guano release large amounts of phosphates, along with other nutrients, which then leach into lower soil horizons. These phosphates combine with nitrogen, calcium, and magnesium to form more stable minerals such as struvite and fluoroapatite, the binding of these cations contributes to the significant decreases in the soil pH in deeper horizons (Tatur, 1989). Detection of these mineral formations in future mineralogical studies will help to confirm the presence of ornithogenic soils.

In some of the ornithogenic soils of Cierva Point, the lower pH in relation to calcium phosphate formation was relatively minimal, such as in CP11 and CP20 where pH dropped by less than 0.5 with depth (Table 4). However, in other ornithogenic soils, such as CP12, CP13, CP14, and CP26, pH values decreased by up to 3.0 with depth, going from nearly neutral to highly acidic in the space of a few centimeters below the ground surface. Mataloni *et al.* (2010), also compared nutrient accumulations and pH values between bare and ornithogenic soils on

Cierva Point. Similar to this study, they found large accumulations of phosphorus and calcium, along with high pH values at the soil surface; however, only the top centimeter of the soil surface was examined, thus the transition to very acidic conditions in deeper horizons of the ornithogenic soils were not discovered in that study. The pH values measured on Cierva Point were some of the most acidic ornithogenic-derived soils reported along the Antarctic Peninsula; other ornithogenic soil along the Antarctic Peninsula had pH values ranging between 3.5 and 5.0 (Simas *et al.*, 2007; Moura *et al.*, 2012; Mendonça *et al.*, 2013). Only in soils with known sulfide sources, such as those on Seymore Island, were pH values as low as those measured on Cierva Point (Souza *et al.*, 2014). Ornithogenic acidity values measured for this study correspond to values reported from previous studies conducted on Cierva Point (Mataloni *et al.*, 2010).

Phosphorus accumulations at the surface or just below the surface of ornithogenic soils were at amounts at least double that of any other examined acidic soil on Cierva Point (Table 4). The high accumulations of phosphorus follow the findings of several other nutrient studies in ornithogenic soils along the Antarctic Peninsula (Tatur, 1989; Simas *et al.*, 2007; Moura *et al.*, 2012; Souza *et al.*, 2014). In all cases the large accumulations of phosphorus are attributed to the mineralization of penguin guano. The only exceptions to the consistently high phosphorus accumulation in ornithogenic soils were at locations CP20 and CP26, where surface amounts of phosphorus and calcium were low relative to deeper depths (but still much higher than other soils), suggesting that these sites were sites of abandoned rookeries that had minimal inputs of fresh guano to mineralize. The theory that these two sites were abandoned rookeries is supported by studies conducted by Tatur, 1989. Tatur identified abandoned penguin rookeries along the Antarctic Peninsula through the presence of penguin bones and relict apatite formations. He

found that the high nutrient concentrations at the soil surface were diminished due to leaching loss; however nutrient accumulations in deeper horizons remained significantly elevated.

6. CONCLUSIONS

1. None of the soils of Cierva Point had detectable permafrost; despite the evidence for significant seasonal freezing; mud boils, solifluction lobes, and other forms of patterned; and cryoturbation. Pedogenesis and soil horizonation are minimal in these soils even though there is evidence of seasonal water movement through the soils.

2. Recently deglaciaded (within a few decades) landforms at Cierva Point feature soils with a neutral pH that have formed recently, and activities from nearby penguin rookeries have not been as influential on the chemical composition of these soils as in acidic or ornithogenic soils. Since these soils have not been exposed for a long period of time, cations have not been leached out of the upper horizons, thus the pH of these soils remains neutral or slightly acidic. Phosphorus and carbon accumulations on these recently deglaciaded soils are relatively low when compared to soils that were deglaciaded at an earlier point in time.

3. Acidic soils are the most widely distributed soils on Cierva Point. These soils have been deglaciaded for much longer (more than a century) than the neutral pH soils and have been subject to longer periods of leaching and acidification. While not directly under penguin rookeries, the proximity of these soils to penguin rookeries has created low pH values and elevated phosphorus and carbon accumulations.

4. Some of the thickest mosses reported on the Antarctic Peninsula occur on Cierva Point, and the effects of these thick mosses are apparent in the soils underneath the mosses. Moss-dominated soils were distinguished by dark horizons with rich accumulations of soil organic

matter, especially at the soil surface. The chemical composition of soils under moss was controlled by proximity to the glacier front, similar to non-moss affected soils. Moss-dominated soils typically occurred over acidified soils; however, some moss buildup occurred over some near-glacial (neutral) soils, indicating that current climatic conditions are more conducive to faster moss growth on recently exposed soil and bedrock.

5. Cierva Point is the site of a rookery that is home to several hundred penguins which significantly alters the chemical composition of the underlying soils. Ornithogenic soils of Cierva Point are strongly acidified by the mineralization and leaching of organic acids from penguin guano, resulting in some of the most acidic soil pH values reported throughout the Antarctic Peninsula. Accumulations of phosphorus and calcium in ornithogenic soils were also several times that of non-ornithogenic soils, due to the mineralization of calcium phosphates in penguin guano.

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Table 1

Pedon ID	Latitude (South)	Longitude (West)	Elevation (m)	Parent Material	Landform
CP01	64°09'41.8"	060°57'06.2"	183	Till over bedrock	Infilled bedrock depression
CP02	64°09'37.9"	060°56'35.0"	153	Till	Moraine
CP03	64°09'49.3"	060°57'12.1"	270	Scree	Block field
CP04	64°09'50.9"	060°56'55.5"	301	Residuum	Ridgetop
CP05	64°09'38.5"	060°57'31.3"	141	Moss over bedrock	Moss bed
CP06	64°09'34.2"	060°57'38.1"	75	Colluviated till	Colluvial hillslope
CP07	64°09'32.7"	060°56'33.6"	88	Scree	Colluvial hillslope
CP08	64°09'25.2"	060°56'28.8"	23	Marine alluvium over till	Beach
CP09	64°09'32.0"	060°56'38.4"	89	Moss over basalt	Mucky depressions
CP10	64°09'31.7"	060°56'54.4"	86	Till	Nivation terrace
CP11	64°09'25.9"	060°57'24.2"	80	Till	Nivation terrace
CP12	64°09'28.8"	060°57'02.3"	68	Till	Nivation terrace
CP13	64°09'27.6"	060°57'17.2"	52	Till	Nivation terrace
CP14	64°09'27.0"	060°57'13.8"	43	Till	Nivation terrace
CP16	64°09'29.1"	060°57'05.5"	45	Organic over colluviated till	Moss upland
CP17	64°09'32.3"	060°57'07.0"	80	Till	Cirque
CP18	64°09'32.3"	060°57'06.2"	79	Colluviated till	Colluvial hillslope
CP19	64°09'27.1"	060°57'09.6"	43	Colluviated till	Colluvial hillslope
CP20	64°09'21.2"	060°57'27.0"	29	Lacustrine	Relict pond
CP21	64°09'25.9"	060°57'32.0"	56	Organic	Moss Upland
CP23	64°09'28.4"	060°57'12.4"	65	Colluvial organics over till	Organic colluvial fan
CP25	64°09'43.4"	060°57'10.8"	188	Colluvium	Solifluction lobe
CP26	64°09'31.3"	060°57'19.5"	87	Lacustrine	Relict pond
CP27	64°09'28.8"	060°57'00.7"	50	Colluvial till	Streamcut hillslope

Table 2

Pedon ID	Depth (cm)	Soil Taxonomy	Slope Class	Vegetation*	Remarks
CP01	40	Lithic Dystrogelepts	Steep		
CP02	106	Typic Gelorthents	Undulating		
CP03	70	Typic Gelorthents	Undulating		Non-sorted polygons
CP04	17	Typic Gelorthents	Level		Frost boils
CP05	39	Lithic Cryofolists	Rolling	Moss	Avian nesting
CP06	52	Typic Humigelepts	Steep		Folistic epipedon
CP07	50	Lithic Humigelepts	Steep	Moss	
CP08	70	Aquic Gelorthents	Level		
CP09	80	Lithic Cryosaprists	Level	Moss	Histic epipedon
CP10	50	Lithic Humigelepts	Level		Penguin rookery
CP11	45	Aquic Humigelepts	Level		Adjacent to rookery
CP12	85	Typic Gelorthents	Moderately steep		
CP13	50	Typic Gelorthents	Gently sloping		
CP14	50	Typic Gelorthents	Strongly sloping		
CP15	100	Typic Humigelepts	Level		
CP16	75	Typic Humigelepts	Steep	Moss	
CP17	80	Aquic Humigelepts	Gently sloping		
CP18	72	Typic Gelorthents	Moderately steep		
CP19	80	Typic Gelorthents	Gently sloping		
CP20	60	Typic Gelaquents	Level	Algae	Relict cryoturbation
CP21	33	Lithic Cryofolists	Strongly sloping	Moss	
CP22	18	Lithic Cryosaprists	Level	Moss	
CP23	90	Typic Humigelepts	Very steep	Moss	
CP24	48	Typic Gelorthents	Gently sloping		Skua nesting site
CP25	60	Lithic Humigelepts	Steep		Penguin nesting
CP26	50	Typic Gelorthents	Level		Clay films
CP27	65	Typic Humigelepts	Steep	Moss	Subsoil extremely red

Depth = Sampling depth
 *Coverage of indicated vegetation are 100%

Table 3

Horizon	Depth (cm)	Dry Color	Sand (%)	Silt (%)	Clay (%)	Texture
<i>Neutral Soils</i>						
CP01 – Lithic Dystrogelept						
A	0-15	strong brown (7.5YR 4/6)	74	22	4	Sandy Loam
Bw1	15-27	dark brown (7.5YR 3/4)	74	24	2	Loamy Sand
Bw2	27-40	brown (7.5YR 4/4)	70	28	2	Sandy Loam
CP02 – Typic Gelorthent						
C1	0-6	dark greyish brown (2.5Y 4/2)	84	12	4	Loamy Sand
C2	6-57	olive brown (2.5Y 4/3)	80	12	8	Loamy Sand
C3	57-70	greyish brown (10YR 5/2)	78	14	8	Sandy Loam
C4	70-106	-	-	-	-	-
CP03 – Typic Gelorthent						
A	0-10	dark reddish brown (5YR 3/2)	96	6	2	Sand
Bw	10-19	yellowish red (5YR 4/6)	92	6	2	Sand
BC	19-31	reddish brown (5YR 4/4)	70	25	5	Sandy Loam
2C1	31-70	dark reddish brown (5YR 3/4)	-	-	-	-
2C2	70-100	-	-	-	-	-
2Crt	100-140	-	-	-	-	-
CP08 – Aquic Gelorthent						
C	0-30	-	-	-	-	-
2Cg	30-70	grey (5Y 5/1)	82	16	2	Loamy Sand
<i>Acidic Soils</i>						
CP04 – Typic Gelorthent						
A	0-6	dark reddish brown (5YR 2.5/2)	-	-	-	-
AB	6-13	dark reddish brown (5YR 3/2)	65	10	25	Sandy Clay Loam
Bw	13-17	dark reddish brown (5YR 3/3)	60	15	25	Sandy Clay Loam
CP06 – Typic Humigelept						
A1	0-22	dark brown (7.5YR 3/3)	72	12	16	Sandy Loam
2A2	22-38	dark brown (7.5YR 3/2)	60	24	16	Sandy Loam
2C1	38-52	dark brown (7.5YR 3/4)	86	12	2	Sand
2C2	52-80	dark yellowish brown (10YR 4/4)	92	6	2	Sand
CP10 – Lithic Humigelept						
A1	0-10	dark brown (10YR 3/3)	86	12	2	Sand
A2	10-22	brown (10YR 3/2)	78	20	2	Loamy Sand
Bw	22-34	olive brown (2.5Y 4/3)	72	22	6	Sandy Loam
C	34-50	light olive brown (2.5Y 5/3)	79	24	6	Sandy Loam
CP17 – Aquic Humigelept						
A1	0-8	dark brown (10YR 3/3)	-	-	-	-
A2	8-28	dark brown (10YR 3/3)	74	14	12	Sandy Loam
A/C	28-53	dark brown (10YR 3/3)	78	18	4	Loamy Sand
C	53-66	light olive brown (2.5Y 5/3)	72	22	6	Sandy Loam
Cg1	66-80	grayish brown (2.5Y 5/2)	72	22	6	Sandy Loam
CP18 – Typic Gelorthent						
A	0-13	brown (10YR 3/2)	80	16	4	Loamy Sand
Bw	13-23	dark yellowish brown (10YR 4/4)	86	12	2	Sand
BC	23-34	yellowish brown (10YR 5/4)	90	8	2	Sand
C1	34-55	brown (10YR 5/3)	92	6	2	Sand
C2	55-72	brown (10YR 5/3)	-	-	-	-
CP19 – Typic Gelorthent						
A	0-9	brown (10YR 4/3)	86	12	2	Sand
E	9-25	brown (7.5YR 5/4)	82	14	4	Loamy Sand
Bw	25-40	strong brown (7.5YR 4/6)	88	8	4	Sand
2BC	40-80	strong brown (7.5YR 4/6)	-	-	-	-

Moss-Dominated Soils

CP05 – Lithic Cryofolist

Oi	0-14	dark red (2.5YR 3/6)	-	-	-	-
Oe	14-36	very dusky red (2.5YR 2.5/2)	-	-	-	-
Oa	36-39	reddish black (2.5YR 2.5/1)	-	-	-	-

CP07 – Lithic Humigelept

D	0-10		-	-	-	-
A1	10-30	dark brown (7.5YR 3/2)	90	8	2	Sand
A2	30-50	dark brown (7.5YR 3/2)	64	34	2	Sandy Loam

CP09 – Lithic Cryosaprist

Oa1	0-18	-	56	20	24	Sandy Clay Loam
Oa2	18-32	-	76	16	8	Sandy Loam
Oa3	32-45	-	60	28	12	Sandy Loam
Oa4	45-80	-	-	-	-	-

CP16 – Typic Humigelept

Oi1	0-11	dark reddish brown (2.5YR 2.5/3)	-	-	-	-
Oi2	11-19	dark reddish brown (2.5YR 2.5/4)	-	-	-	-
A	19-39	very dusky red (10R 2.5/2)	92	4	4	Sand
Bs	39-62	dark reddish brown (5YR 3/3)	72	24	4	Sandy Loam
BC	62-75	reddish brown (5YR 4/4)	76	20	4	Loamy Sand

CP21 – Lithic Cryofolist

Oi	0-15	reddish brown (2.5YR 4/4)	-	-	-	-
Oe	15-22	dusky red (2.5YR 3/2)	-	-	-	-
Oa	22-33	reddish black (2.5YR 2.5/1)	-	-	-	-

CP23 – Typic Humigelept

Oa1	0-29	very dusky red (2.5YR 2.5/2)	80	5	15	Sandy Loam
Oa2	29-46	dusky red (2.5YR 3/2)	80	7	13	Sandy Loam
2Bw	46-90	dark red (2.5YR 3/6)	-	-	-	-

CP25 – Lithic Humigelept

Oi	0-9	yellowish red (5YR 4/6)	-	-	-	-
A1	9-15	dark reddish brown (5YR 3/3)	-	-	-	-
A2	15-26	dark reddish brown (5YR 3/2)	82	8	10	Loamy Sand
A3	26-34	dark reddish brown (5YR 2.5/2)	82	10	8	Loamy Sand

CP27 – Typic Humigelept

Oe	0-8	dark reddish brown (5YR 3/3)	-	-	-	-
A	8-24	very dusky red (10R 2.5/2)	80	12	8	Loamy Sand
AB	24-39	dusky red (10R 3/3)	88	8	4	Sand
Bw	39-51	dark reddish brown (5YR 3/4)	96	2	2	Sand
BC	51-65	dark reddish brown (5YR 3/3)	92	6	2	Sand

Ornithogenic Soils

CP11 – Aquic Humigelept

A1	0-7	very dark grey (10YR 3/1)	73	11	16	Sandy Loam
A2	7-18	dark brown (10YR 3/3)	78	8	14	Sandy Loam
Bw	18-35	brown (7.5YR 4/4)	84	12	4	Loamy Sand
Cd	35-45	light olive brown (2.5Y 5/3)	72	22	6	Sandy Loam
Cg	45-100	greyish brown (2.5Y 5/2)	-	-	-	-

CP12 – Typic Gelorthent

A1	0-4	brown (10YR 4/3)	-	-	-	-
A2	4-9	dark brown (7.5YR 3/4)	-	-	-	-
A3	9-25	strong brown (7.5YR 4/6)	80	8	2	Sand
E	25-42	brown (7.5YR 5/4)	88	10	2	Sand
Bw1	42-53	strong brown (7.5YR 5/6)	94	4	2	Sand
Bw2	53-85	dark yellowish brown (10YR 4/4)	82	14	4	Loamy Sand
BC	85-100	-	-	-	-	-

CP13 – Typic Gelorthent

A	0-3	brown (10YR 3/2)	-	-	-	-
C1	3-50	dark yellowish brown (10YR 4/4)	-	-	-	-
C2	50-100	brown (10YR 4/3)	-	-	-	-
CP14 – Typic Gelorthent						
A1	0-3	yellowish brown (10YR 5/4)	-	-	-	-
A2	3-14	brown (10YR 3/2)	86	6	8	Loamy Sand
Bw	14-28	brown (10YR 4/3)	84	12	4	Loamy Sand
C	28-50	brown (10YR 5/3)	76	16	8	Sandy Loam
CP20 – Typic Gelaquent						
Oi	0-4	yellowish brown (10YR 5/6)	-	-	-	-
A1	4-15	very dark greyish brown (10YR 3/2)	-	-	-	-
A2	15-30	grayish brown (10YR 5/2)	82	8	10	Loamy Sand
A2	30-35	dark brown (10YR 3/3)	70	22	8	Sandy Loam
Cg1	15-30	grey (10YR 5/1)	94	4	2	Sand
Cg2	35-60	dark brown (10YR 3/3)				
CP26 – Typic Gelorthent						
A	0-12	dark brown (7.5YR 3/2)	65	10	25	Sandy Clay Loam
Bw1	12-28	dark reddish brown (5YR 3/4)	40	24	36	Clay Loam
Bw2	28-40	dark reddish brown (5YR 3/3)	32	32	36	Clay Loam
BC	40-50	brown (10YR 4/3)	33	34	33	Clay Loam

Soil physical property descriptions not available for CP15, CP22, CP24

Missing data represents horizons that were not sampled, completely organic, or too thin for full description

Table 4

Horizon	Depth (cm)	pH (water)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Na (mg/kg)	SOC (g/kg)	EC (μS/cm)
Neutral Soils											
CP01 – Lithic Dystrogelept											
A	0-15	6.3	565	1926	4213	3375	18648	15948	204	5	5.8
Bw1	15-27	6.8	810	1663	4328	4018	22828	17398	291	7	5.2
Bw2	27-40	6.7	712	2765	4208	3900	22328	22033	416	11	6.9
CP02 – Typic Gelorthent											
C1	0-6	7.5	250	1035	13453	2199	12123	13233	222	4	28.2
C2	6-57	8.3	259	1051	18370	3165	13468	14508	248	3	16.3
C3	57-70	7.9	266	1002	16878	3283	13425	13860	283	3	18.6
C4	70-106	-	-	-	-	-	-	-	-	-	-
CP03 – Typic Gelorthent											
A	0-10	5.2	452	532	2033	2305	14798	9000	283	8	8.8
Bw	10-19	5.3	346	566	2840	1857	14973	10280	255	7	5.2
BC	19-31	5.9	383	1283	8625	2815	16295	20070	323	3	9.2
2C1	31-70	-	-	-	-	-	-	-	-	-	-
2C2	70-100	-	-	-	-	-	-	-	-	-	-
2Crt	100-140	-	-	-	-	-	-	-	-	-	-
CP08 – Aquic Gelorthent											
C	0-30	-	-	-	-	-	-	-	-	-	-
2Cg	30-70	7.2	373	988	4670	3548	16150	9518	494	0	10.3
Acidic Soils											
CP04 – Typic Gelorthent											
A	0-6	4.6	1504	1024	2372	2305	16918	9840	439	122	44.5
AB	6-13	4.6	1172	880	2258	3115	21980	10848	445	57	16.0
Bw	13-17	5.1	1397	720	3193	4785	28800	18715	818	55	7.3
CP06 – Typic Humigelept											
A1	0-22	4.1	7978	1606	3683	1639	15570	14833	474	103	101.5
2A2	22-38	4.0	12535	1806	6190	2625	27275	19693	398	35	26.9
2C1	38-52	4.0	3410	1896	3210	2630	19220	13330	164	7	22.2
2C2	52-80	4.1	1603	1309	2660	2465	16460	8638	154	3	13.9
CP10 – Lithic Humigelept											
A1	0-10	4.3	4613	1352	4773	2838	15928	11908	405	19	174.9
A2	10-22	4.2	5690	1195	4665	3108	18038	13418	369	12	76.6
Bw	22-34	4.6	1391	1519	3740	3275	15925	12798	215	3	12.2
C	34-50	4.6	1300	1571	3518	3373	16448	12480	216	1	9.5
CP17 – Aquic Humigelept											
A1	0-8	3.8	8820	1675	4820	2486	18418	16970	601	81	280
A2	8-28	3.6	8163	1682	4878	3010	21340	18338	527	56	59.0
A/C	28-53	3.8	4331	1073	2937	3534	12405	14175	357	16	49.9
C	53-66	3.9	2441	1458	3318	3148	10305	13990	215	9	35.6
Cg1	66-80	3.9	1538	1113	3091	3199	10545	12420	159	4	23.1
CP18 – Typic Gelorthent											
A	0-13	3.5	7650	1363	3828	1411	12420	10060	293	45	112.6
Bw	13-23	3.7	4933	1293	2067	1853	11565	9855	154	13	38.0
BC	23-34	3.6	4531	1144	1688	2211	11930	10660	162	4	51.6
C1	34-55	3.5	5635	1249	1660	2293	13680	11600	162	3	59.4
C2	55-72	-	-	-	-	-	-	-	-	-	-
CP19 – Typic Gelorthent											
A	0-9	4.9	5895	1327	1293	450	8760	6375	249	11	46.1
E	9-25	3.6	9585	2067	1204	797	11725	10515	177	5	42.1
Bw	25-40	3.5	5125	1750	1277	1292	9635	9880	182	6	44.4
2BC	40-80	-	-	-	-	-	-	-	-	-	-

Moss-Dominated Soils

CP05 – Lithic Cryofolist

Oi	0-14	-	639	492	4098	1991	949	738	476	342	-
Oe	0-36	-	1250	337	4337	800	2546	2682	336	334	-
Oa	36-39	-	2284	429	2260	382	5650	5678	267	268	-

CP07 – Lithic Humigelept

D	0-10	-	-	-	-	-	-	-	-	-	-
A1	10-30	5.3	1515	1072	5150	4125	20383	13980	371	17	15.1
A2	30-50	6.2	2148	1266	7463	4925	22815	20298	567	23	5.2

CP09 – Lithic Cryosaprist

Oa1	0-18	5.3	4860	657	7070	3140	24400	22403	738	122	14.4
Oa2	18-32	5.8	5465	525	8495	2282	13633	23093	664	131	19.3
Oa3	32-45	5.8	3628	643	7858	3798	24050	20678	908	119	14.2
Oa4	45-80	-	-	-	-	-	-	-	-	100	-

CP16 – Typic Humigelept

Oi1	0-11	-	3040	80	1071	105	926	9192	60	318	-
Oi2	11-19	-	5884	153	943	126	4008	12674	67	315	-
A	19-39	3.4	4535	1649	1425	1595	18888	10478	178	49	52.4
Bs	39-62	3.6	4340	2778	1147	1278	20288	11380	81	9	44.5
BC	62-75	3.6	3043	2043	1344	2225	20810	11320	101	5	59.7

CP21 – Lithic Cryofolist

Oi	0-15	-	609	341	2304	1284	325	221	412	340	-
Oe	15-22	-	1100	163	6320	792	2728	1956	253	342	-
Oa	22-33	4.1	5120	371	4131	655	13390	8005	370	290	75.6

CP23 – Typic Humigelept

Oa	0-29	3.5	6785	396	756	533	7465	10110	204	148	151
Oa2	29-46	3.6	11855	551	827	857	12090	14565	225	91	88
2Bw	46-90	4.0	3967	728	1184	1593	10005	7770	120	18	16.8

CP25 – Lithic Humigelept

Oi	0-9	-	692	497	6596	1456	475	433	282	358	-
A1	9-15	4.7	1242	467	3967	3108	14405	8985	359	80	46.3
A2	15-26	5.2	1467	510	3984	3486	15915	11740	503	64	14.1
A3	26-34	5.4	1614	798	5960	3893	23108	14443	641	61	15.1

CP27 – Typic Humigelept

Oe	0-8	4.5	-	-	-	-	-	-	-	112	205
A	8-24	3.4	2711	752	1026	1724	11845	7115	199	40	128.7
AB	24-39	3.5	2803	736	1030	2076	12435	8720	141	23	84.9
Bw	39-51	3.8	1473	679	976	2350	11515	12800	103	7	27.7
BC	51-65	3.7	1691	1283	638	1007	10765	8800	74	4	40.3

Ornithogenic Soils

CP11 – Aquic Humigelept

A1	0-7	3.8	24223	1555	24298	1011	12763	16543	791	77	215
A2	7-18	3.6	34725	1131	23045	943	19285	23955	582	70	118.5
Bw	18-35	3.3	3268	1086	1961	1125	15523	5098	230	13	78.5
Cd	35-45	3.4	5008	1439	2883	1665	16348	8930	148	13	66.3
Cg	45-100	-	-	-	-	-	-	-	-	-	-

CP12 – Typic Gelorthent

A1	0-4	6.3	47150	3388	82425	5053	8983	10183	1220	159	628
A2	4-9	3.8	12503	2272	12843	894	10633	9425	601	133	890
A3	9-25	3.5	10943	2123	5080	495	16710	9130	399	27	176
E	25-42	3.5	4433	1233	2222	900	15533	5585	243	4	104
Bw1	42-53	3.4	3228	1128	2059	1161	15945	5273	237	3	73.1
Bw2	53-85	3.3	3938	1264	1980	1175	17010	5958	189	4	81.5
BC	85-100	-	-	-	-	-	-	-	-	-	-

CP13 – Typic Gelorthent

A	0-3	5.2	15065	1368	12438	1748	10075	10258	496	133	977
C1	3-50	4.0	5008	1555	2263	999	13005	6758	404	38	136.5
C2	50-100	3.6	8320	1693	2069	833	20555	8733	395	48	64.8
CP14 – Typic Gelorthent											
A1	0-3	5.1	37275	2042	64750	1335	11045	13590	1137	107	680
A2	3-14	4.3	29600	1298	49300	882	11648	11060	708	65	229
Bw	14-28	3.9	11338	2166	11503	797	16990	10140	303	25	83.7
C	28-50	3.7	5998	1915	2499	1132	18943	8243	204	5	67.8
CP20 – Typic Gelaquent											
Oi	0-4	-	6392	611	10009	738	1074	2087	216	202	-
A1	4-15	4.6	15415	799	16895	704	5595	7125	434	88	254
A2	15-30	4.3	31235	955	38095	787	7285	10255	722	-	24.6
Cg1	30-35	4.7	32240	1427	29890	1067	10875	15660	832	59	78.9
Cg2	35-60	4.5	4912	910	1211	598	5380	4755	142	2	47.1
CP26 – Typic Gelorthent											
A	0-12	5.4	1513	505	3612	3461	15130	12295	524	175	60.4
Bw1	12-28	5.2	36620	1646	19915	1870	15805	26075	989	94	34.3
Bw2	28-40	4.5	41745	1639	16785	1047	15230	30685	693	81	48.8
BC	40-50	4.6	29985	1369	9515	2086	16875	24775	813	39	26.2

Soil chemical properties not available for CP15, CP22, CP24

Missing data represents horizons that were not sampled, completely organic, or too thin for analysis

All elemental analyses were from Mehlich 1 extracts

Data corrected for mass of soil used

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure Captions

Figure 1: Cierva Point Map. Modified from ASPA No. 134, 2013.

Figure 2: Soil Profile Locations. Location of the twenty-four described and categorized soils on Cierva Point. Colors represent different soil categories: blue for neutral soils, red for acidic soils, green for moss-dominated, and yellow for ornithogenic soils. Satellite image of Cierva Point modified from Google Earth's 2014 Digitalglobe image.

Figure 3: Representative Soil Categories. Four soil groups found on Cierva Point, Antarctica. Acidic soils (a) CP19, Typic Gelorthent. Neutral soils (b) CP03, Typic Gelorthent. Moss-dominated soils (c) CP25, Lithic Humigelept. Ornithogenic soils (d) CP26, Typic Gelorthent.

Figure 4: Soil pH. Comparison of average soil pH values among four identified soil categories (Neutral, Acidic, Moss-Dominated, Ornithogenic). Soil pH for each sample location was determined by a weighted average (by horizon thickness) of the pH from each horizon. The neutral category was the average of four soils, while acidic and ornithogenic categories were the average of six soils, and the moss-dominated category was the average of eight soils.

Figure 5: High Elevation Soils. Image taken from the highest examined area of Cierva Point (330 m a.s.l.), picture taken facing west. Located in the image (black box) was the highest elevation soils found on the peninsula (CP04 at 300 m a.s.l.), in a potentially unglaciated bedrock depression.

Figure 6: Soil Organic Matter Buildup. Comparison of average soil organic matter buildup among four identified soil categories (Neutral, Acidic, Moss-Dominated, Ornithogenic).

The neutral category was the average of four soils, while acidic and ornithogenic categories were the average of six soils, and the moss-dominated category was the average of eight soils. Organic matter buildups in the moss-dominated soils were significantly higher than the other three categories, which had virtually no buildups.

Figure 7: Soil Phosphorus. Comparison of average soil phosphorus among four identified soil categories (Neutral, Acidic, Moss-Dominated, Ornithogenic). Soil phosphorus for each sample location was determined by a weighted average (by horizon thickness) of the phosphorus from each horizon. The neutral category was the average of four soils, while acidic and ornithogenic categories were the average of six soils, and the moss-dominated category was the average of eight soils.

List of Tables

Table 1: Location, parent material and landform setting for sampled soil profiles.

Table 2: Location characteristics, profile depth and classification for sampled soils.

Table 3: Cierva Point soil horizon physical properties.

Table 4: Cierva Point soil horizon chemical properties.