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Hyperarid Soils and the Soil Taxonomy

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In the past decade, pedological research in hyperarid environments worldwide has revealed landscapes and soil features that are regionally prevalent and distinctive, but not well captured in the current soil taxonomy. Hyperarid soils bear genetic features that can differ considerably from those in more humid desert environments. In particular, they often contain horizons cemented with halite (NaCl) or heavily enriched with nitratine ($NaNO_3$). Unlike soils commonly found in more humid regions, they may also lack most vascular plants, pedogenic carbonates, and biotic mixing processes. Based on the global occurrence of indurated salic horizons and nitric horizons in hyperarid soils, we propose that the soil taxonomy be amended to include a petrosalic diagnostic subsurface horizon, a nitric diagnostic subsurface horizon, and Petrosalids great group within the Aridisols order. Additionally, we suggest the definition and establishment of a Hyperaridic Soil Moisture Regime (SMR). In this paper, we use soils from the Atacama Desert to illustrate how pedogenesis in extreme hyperarid environments differs from that in more humid environments, and we review the current literature regarding soils in other hyperarid locations with indurated soluble salt horizons. The changes proposed here would create a more encompassing classification system for the Earth's desert regions, improving our ability to clearly communicate relevant genetic, ecological, and economic information to both land-managers and researchers.

Abbreviations: P, precipitation; PET, potential evapotranspiration; SMR, soil moisture regime.

The soil taxonomy has undergone much evolution, particularly within the Aridisol order, since its initial publication in 1975 (Yaalon, 1995). As soils of previously understudied regions are examined, pedological features may be discovered that are inadequately described within the existing soil taxonomy (Soil Survey Staff, 1999). Many earth and ecological scientists rely on the taxonomic nomenclature of a soil to derive significant information about its origin and utility (Schimel and Chadwick, 2013). It is therefore important that the soil taxonomy continue to reflect current research and understanding if it is to remain pertinent and useful to scientists globally.

Much of the criteria currently used to classify Aridsols are derived from the deserts of western North America that span a broad range of altitudes, latitudes, temperatures, and moisture. The majority of this region is arid, with precipitation (P) to potential evapotranspiration (PET) ratios of 0.05 to 0.2. While challenging to life, plant available moisture can be available for significant periods of time and water is available to move downward under unsaturated flow. In contrast, international research in the past few decades has begun to reveal the pedological features of hyperarid environments (P/PET < 0.05; e.g., Amit and Yaalon, 1996; Ewing et al., 2006; Quade et al., 2007; Bockheim and McLeod, 2008). These soils bear genetic

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features considerably different from those in more humid environments, such as the deserts of North America. First, the landscapes lack or have minimal plant cover. A striking illustration of this is to compare Google Earth imagery to the distribution of a hyperarid climate shown in Fig. 1—the low imprint of biology is striking. As a consequence of minimal plant cover, the cycling of organic matter and biotic mixing processes in these soils are largely absent. Additionally, in the more extreme hyperarid regions there is little leaching of the most soluble salts from the soil profile. In most North American deserts, soils have minor amounts of sulfates and even smaller quantities of more soluble salts such as halite. In contrast, the prolonged lack of P in certain hyperarid environments has produced landscapes with solute accumulations far exceeding that found in more humid deserts. In the Atacama Desert for example, the near-continuous hyperaridity has preserved Pliocene-aged fluvial landforms and soils cemented with combinations of sulfates, chlorides, and nitrates (Rech et al., 2006; Amundson et al., 2012). Similarly, soils in different regions of Antarctica contain horizons cemented with nitrates, chlorides, and sulfates (Bockheim, 2014), and Pleistocene soils cemented with chlorides have been identified in the Negev Desert (Amit and Yaalon, 1996).

The present soil taxonomy lacks diagnostic horizons for soil horizons cemented with halite (NaCl) or enriched with nitratine ($NaNO_3$). More fundamentally, it lacks a way to distinguish the unique pedogenesis that occurs in hyperarid environments. Here we suggest that these omissions hinder the ability of scientists and researchers to convey the pedologic history and utility of these soils, which are found across the globe. In this paper we examine and discuss soils from the Atacama Desert in relation to their formation and classification as an illustrative example of hyperarid pedogenesis. We then summarize the literature on indurated salic and nitric horizons, and consider how the soil taxonomy might be amended to accommodate them.

CURRENT SOIL TAXONOMY

The current soil taxonomy includes diagnostic horizons for a range of salts: $CaCO_3$ (calcic), $CaSO_4{\cdot}2H_2O$ (gypsic), and salts more soluble than gypsum (salic). To qualify, horizons with these salts are required to be at least 15 cm thick, non-cemented, and contain a threshold amount of the given salt (Soil Survey Staff, 1999). While gypsic and calcic horizons are specific to sulfate and carbonate respectively, salic horizons include all salts more soluble than gypsum. There is currently no means to designate a salic horizons composed primarily of halite or nitrate.

In addition to these diagnostic horizons, there are also petrogypsic and petrocalcic horizons that are cemented. Indurated gypsic and calcic horizons are defined by their lateral continuity, induration, and thickness (Soil Survey Staff, 1999). An indurated horizon is important in the soil taxonomy because it is indicative of great antiquity, restricted plant growth, and considerable limitations to the use of the soil. The current soil taxonomy does not, however, include an indurated salic (petrosalic) horizon, which in some hyperarid deserts is equally as important as petrogypsic and petrocalcic horizons.

Finally, the Aridic SMR is currently the most water-limiting in the soil taxonomy and includes soils in both aridic and hyperaridic climates. In normal years these soils are defined as dry (in the control section) more than 50% of the time while soil temperatures are above 5°C at 50-cm depth and some or all parts of the soil are moist less than 90 consecutive days when the soil temperature is above 8°C at 50-cm depth (Soil Survey Staff, 1999).

Global Distribution of Hyperaridity and Indurated Salic and Nitric Horizons

Aridity (in the climatological sense), is dependent on the relationship between moisture inputs and moisture losses, and is measured as P/PET. Potential evapotranspiration is calculated

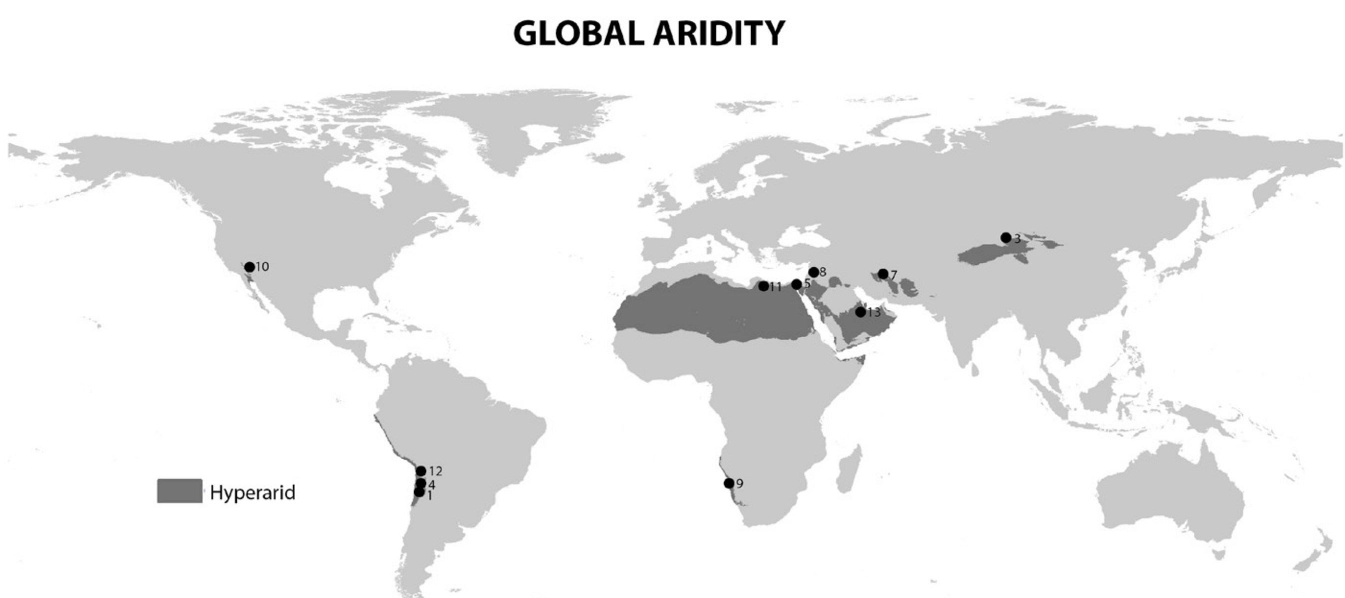

Fig. 1. The global distribution of hypearidity in warm deserts. Points indicate the location of previously described indurated salic or nitric horizons and the numbers correspond to the references listed in Table 1. Soils 2 and 6 are not displayed because the aridity data set did not include values for polar regions. Aridity data set is from Zomer et al. (2008, 2007) and available at http://www.cgiar-csi.org.

Table 1. A selection of publications that have previously described an indurated salic or nitric horizon. Only horizons 10 cm or more in thickness were included. Map number corresponds to the number on Fig. 1. The location of the horizon, either surface or subsurface, indicates the direction of water flow (downward vs. upward, respectively). The original term used to describe the horizon is noted alongside the designation proposed in this study.

Map number	Location	Location of horizon	Descriptive term used	Proposed horizon name	Reference
1	Atacama Desert, Chile	Subsurface	Nitric Horizon	Nitric	Ewing et al., 2006
2	Dry Valleys, Antarctica	Subsurface	Nitric Horizon	Nitric	Bockheim, 1997
3	Turpan-Hami area, China (Gobi Desert)	Subsurface	Nitric Horizon	Nitric	Qin et al., 2012
4	Atacama Desert, Chile	Subsurface	Salic Horizon	Petrosalic	Ewing et al., 2006
5	Negev Desert, Israel	Subsurface	Petrosalic Horizon	Petrosalic	Amit and Yaalon, 1996
6	Dry Valleys, Antarctica	Subsurface	Petrosalic Horizon	Petrosalic	Bockheim, 1997
7	Kerman, Iran (Bam Area)	Subsurface	Petrosalic Horizon	Petrosalic	Moghiseh and Heidari, 2012
8	Azran, Jordan (Syrian Desert)	Subsurface	Extremely Hard Salic Horizon	Petrosalic	Khresat and Qudah, 2006
9	Namib Desert, Namibia	Subsurface	Pedogenic Halite Crust	Petrosalic	Watson, 1983
10	Death Valley, USA	Surface	Rock Salt	Petrosalic	Hunt et al., 1966
11	Libyan Desert, Egypt	Surface	Salt Crust	Petrosalic	Aref et al., 2002
12	Atacama Desert, Chile	Surface	Petrosalic Horizon	Petrosalic	This paper
13	Arabian Desert, Saudi Arabia	Surface	Blocky Salt Crust	Petrosalic	Goodall et al., 2000

from measurements of mean monthly temperatures and the average number of daylight hours per month. At values of P/PET < 0.05, a region is considered to be hyperarid. Figure 1 shows the global distribution of hyperaridity. In 1997, the United Nations Environmental Program concluded that 7.5% of the Earth's land surface is hyperarid and an additional 12.1% is arid (UNEP, 1997).

Indurated salt crusts are widespread and described in the literature by pedologists and sedimentologists, both in hyperarid and arid regions (Fig. 1 and Table 1). Many of them are present in playas and undergo dynamic cycles of dissolution during the rainy season and recrystallization during the dry season. In contrast, P events in hyperarid regions where rainfall is <100 mm yr^{-1} are too infrequent and insufficient to fully dissolve salt accumulation. This prolonged moisture deficit allows for the growth of thick indurated surface horizons from evaporating water.

The location of the horizon within the profile is dependent on the direction of water movement. Well-drained soils with downward migrating water develop petrosalic horizons in the subsurface. This is the case for Soils 4 through 9 in Table 1. Alternatively, an upward movement of water concentrates very soluble salts at the surface where the petrosalic horizon forms (Soils 10—13 in Table 1). Nitric horizons are widespread in the Atacama Desert, the Dry Valleys of Antarctica, and the Gobi Desert. The origin of these salt deposits has been traced to atmospheric deposition, and the presence of such large deposits signifies great antiquity (Qin et al., 2012).

The lack of nitric and petrosalic horizons in the current soil taxonomy makes it very difficult to determine the distribution of soils with these horizons, as there is no means to denote their presence using the taxonomic nomenclature. As demonstrated in Table 1, a variety terms have been used to describe them both by pedologists and sedimentologists. Regardless of the absence of these diagnostic horizons in the soil taxonomy, some authors have still chosen to use the terminology 'petrosalic' (Amit and Yaalon, 1996; Bockheim, 1997; Moghiseh and Heidari, 2012).

A CASE STUDY OF HYPERARID PEDOGENESIS: THE ATACAMA DESERT

Climate and Geology

The aridity of the Atacama Desert is truly astounding. Geomorphic studies suggest that the Atacama has experienced a near-continuous hyperarid climate since the late Pliocene (Hartley and Chong, 2002; Amundson et al., 2012). Almost all of the land between 15 and 30°S from sea level to 3500 m above sea level is considered hyperarid, which amounts to an area of ~150,000 km^2 (Houston and Hartley, 2003). There are a number of factors that conspire to maintain this extreme climate, including cold upwelling ocean currents, a rain-shadow from the Andes, and a subtropical high-pressure belt (Houston, 2006). It is not uncommon for areas in the region to receive P only once every 10 yr or more. Its tropical latitude leads to small temperature changes between winter and summer months.

While the full diversity of soils in the Atacama Desert is far from understood, this section provides an overview of typical features. Due to long-term and relatively continuous hyperaridity, the Atacama possesses suites of alluvial fans and terraces that are commonly Tertiary in age. Water is limiting for many common pedogenic processes. Even on Pliocene-aged soils chemical weathering, as measured by the formation of Bw or Bt horizons, is almost negligible. The slow but continuous deposition of dust and aerosols infills and physically expands the soils, while the rare rainfall events dissolve the incoming sulfate, chloride, nitrate salts and create soil horizons ordered by solubility of the salt (Ewing et al., 2006). Additionally, carbonates are nearly absent due to the lack of biological soil CO_2 and the dominance of the sulfate anion (Ewing et al., 2006; Quade et al., 2007). In the heart of the Atacama Desert at elevations of 1000 to 1500 m, sulfate horizons overly subsurface horizons enriched in soluble salts, dominantly NaCl with lesser quantities of $NaNO_3$. On older surfaces, both the sulfate and halite/nitrate horizons are indurated (Ewing et al., 2006).

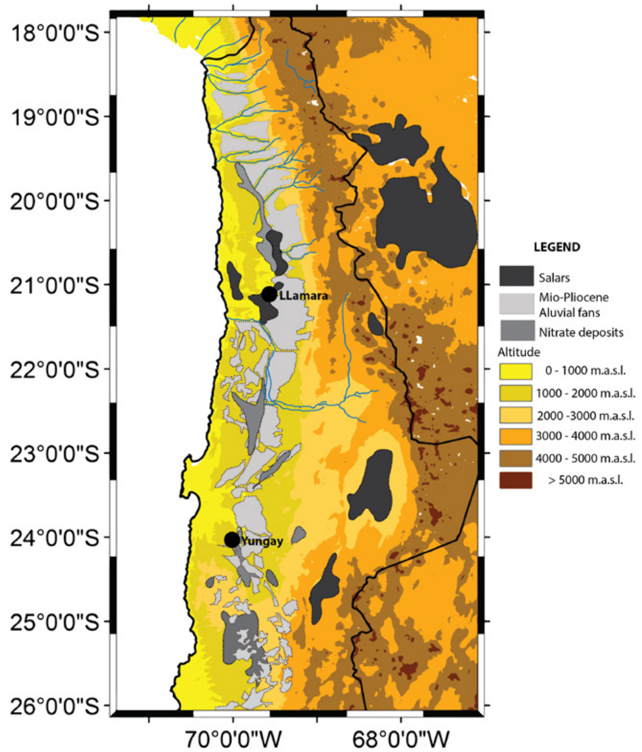

Fig. 2. A map of the Atacama Desert with the location of the Yungay site and the Salar de Llamara sites. Salar deposits are shown in black, nitrate deposits in gray, and Mio-Pliocene alluvial fans in light gray.

These well-drained fans and terraces dominate the landscape and many terminate in internally drained basins. During cooler periods these basins may have formed pluvial lakes from Andean runoff, but as a result of tectonic deformation and prolonged hyperaridity they are now distinctive salt-covered flats or playas known in Spanish as salars. Due evaporative losses of the upward migrating water table, these salars are covered by a dense NaCl crust that continues to react with atmospheric humidity (Ericksen and Salas, 1990). Occasionally due to wind deflation of salts these crusts also are found extending beyond the playa "boundary".

In the Atacama Desert the subsurface pedogenic concentration of salts in the Bzm horizons on well-drained surfaces, particularly nitrates and iodates, are economically mineable resources. Soils containing caliche ore deposits (the local name for nitrate-rich horizons) are estimated to cover 2.8 million hectares of Chilean deserts. These deposits are the only natural source of nitrate in economically significant quantities, and the most concentrated horizons contain 6.5 to 8.5% $NaNO_3$ by weight (Harben and Theune, 2006). From the 19th to the early 20th century these horizons were mined heavily and became one of the largest sources of nitrate (Ericksen, 1981). Additionally, indurated salic horizons contain anomalously high concentrations of iodine (I) and chromium (Cr). Many of these indurated salic horizons contain I concentrations three to four orders of magnitude higher than average continental crust and currently serve as the greatest source of mined I in the world (Perez-Fodich et al., 2014).

In summary, there are two (though likely more) distinctive and widespread pedohydrological regimes: (1) alluvial fans and related terraces dominated by sparse downward soil water movement, and (2) dry lake beds or nearby environs impacted by the upward migration of waters. As we will discuss, being able to distinguish these settings taxonomically is an important objective.

Fig. 3. The Yungay site, a well-drained Mio-Pliocene alluvial fan. This is a very common landscape in the hyperarid Atacama Desert.

Soil Descriptions

Here we discuss three soil pits from the Atacama Desert in nothern Chile representative of the two distinctive geomorphic surfaces described above (Fig. 2). The first soil is from a well-drained, post-Miocene alluvial fan in the Yungay region located near Antofagasta, Chile (Fig. 3). It was first described and reported by Ewing et al. (2006). Rare rainfall events occurring over the past millions of years have distributed atmospheric-derived salts through the profile as a function of their solubility. Porous and very soft gypsic horizons ~20 to 30 cm thick are commonly found on the surface (Table 2). These overly an indurated Petrogypic horizon that extends from 39 to 71 cm. Beneath the Petrogypsic horizon is a salic horizon (85–102 cm), and an indurated salic horizon from 122 to 146 cm. The indurated salic horizon contains ~ 16 kg nitrate m^{-2} and 90 kg chloride m^{-2} (Fig. 5). The current classification of this soil to the subgroup level is a Petrogypsic Haplosalid.

The other two soils are from the Salar de Llamara near Iquique, Chile and represent a short chronosequence of Pleistocene and mid-Holocene soils (Fig. 4). These soil pits were excavated and characterized using standard pedological methods in June 2013 (Soil Survey Staff, 1999). Splits of each horizon were sent to ALS Geochemistry in Reno, NV for total chemical analysis and water extracts were analyzed for SO_4^{2-} and Cl^- using a Thermo Scientific Dionex ICS1500 with an AS25 analytical column (ion chromatography) at University California—Berkeley. Both soils have an indurated salic horizon at the surface comprised almost entirely of halite, which varies in thickness from 51 cm at the Pleistocene site to 22 cm at the Holocene site. Below these horizons are gypsic and a calcic horizons (Fig. 6, Table 2). In contrast to the Yungay site, these soils have experienced a long history of upward migrating water driven by evaporation. This has resulted

Table 2. Horizon descriptions and soluble ion concentrations from the Yungay soil and the Holocene and Pleistocene soils in the Salar de Llamara.

Yungay-Pliocene† Petrogypsic Haplosalid			Salar de Llamara- Holocene Gypsic Haplosalid				Salar de Llamara- Pleistocene Gypsic Haplosalid			
Horizon	Depth	Cl^-	Horizon	Depth	SO_4^{2-}	Cl^-	Horizon	Depth	SO_4^{2-}	Cl^-
	cm	mmol g^{-1} soil		cm	mmol g^{-1} soil			cm	mmol g^{-1} soil	
Bcyk	0–2	0.01	Bzm	0–22	3.07	7.90	Bzm1	0–3	0.23	8.10
Byk1	2–3	0.00	Bz	22–31	4.46	1.07	Bzm2	3–30	1.07	9.06
Byk2	3–12	0.01	Byk1	31–37	3.38	0.14	Bzm3	30–51	0.99	11.28
Byk3	12–26	0.01	Byk2	37–48	3.10	0.06	Bykz	51–65	2.46	0.65
By	26–39	0.01	Byk3	48–61	1.68	0.03	Ck1	65–82	0.55	0.79
Byknzm	39–71	0.19	Bk	61–73	0.28	0.03	Ck2	82–99	0.62	0.54
Bynzk	71–85	0.12	Cky1	73–78	3.19	0.00	Ck3	99–109	0.34	0.23
Byknz	85–102	0.26	Cky2	78–89	3.21	0.00				
Bnzyk	102–122	1.62	Cky3	89–94	3.08	0.03				
Bnzm	122–146	11.58								
Cnzky1	146–154	5.38								
Cknzy1	154–180	0.09								
Cknzy2	180–192	0.06								
Cknzy3	192–211	0.07								
Cknzy4	211–232	0.08								

†Data for the Yungay soil was taken from Ewing et al. (2006).

in a reverse order of salt accumulation with halite on the surface and sulfate deeper in the profile. Both of these soils are classified as Gypsic Haplosalids.

In the present soil taxonomy, the well-drained, post-Miocene soils in the Atacama Desert are commonly classified as Petrogypsic Haplosalids or Typic Petrogypsids depending on the depth of the salic (Bzm) horizon. These designations are insufficient because they confer no information about the presence of an indurated salic horizon, or the mineable quantities of nitrate or iodate. The soils we have observed within the salars are classified as Gypsic Haplosalids. Similarly, these designations provide no insight into the dense and nearly impenetrable halite crust that covers the surface, or the orientation of the gypsic and salic horizons relative to that in the more common well-drained soils. The inclusion of all three of these soils into Haplosalids is problematic. First, it would be highly desirable to distinguish the different soil forming environments and soil characteristics (Fig. 5 vs. 6). Second, both soil types are greatly impacted by indurated salic horizons—the excavation of all of these soils requires the use of a jack hammer. Third, the presence of a rugged and indurated salic horizon on the soil surface is a feature of both pedogenic and practical interest.

Proposed Amendments to the Soil Taxonomy

To better classify the diversity of desert soils such as those described above, and to effectively communicate the management best suited for them, we propose that the soil taxonomy be amended to better represent soils in hyperarid regions. This includes the addition of (i) a petrosalic diagnostic subsurface horizon, (ii) a nitric diagnostic subsurface horizon, and (iii) a Petrosalids great group in the Aridisols order. Additionally, we advocate for the definition and adoption of a Hyperaridic SMR. We suggest that the new diagnostic subsurface horizons be defined as follows:

Petrosalic horizon (Bzm): a horizon at least 10 cm thick which must be cemented or indurated by salts more soluble that gypsum, and because of lateral continuity, roots can penetrate only along vertical fracture with a horizontal spacing of 10 cm or more.

This definition is analogous to that used for the definition of petrogypsic and petrocalcic horizons. The need for a diagnostic petrosalic horizon has been expressed in the past by others (e.g., Bockheim, 1997) and was adopted by the International Union of Soil Scientists in 2007 (IUSS Working Group WRB, 2007). The lack of inclusion in the soil taxonomy thus far may stem from a belief that petrosalic horizons are rare or will slake in water. However these horizons occur in numerous regions of Earth (Table 1) and due to the prolonged extreme aridity under which they have formed will not slake in water.

Nitric horizon (Bz or Bzm): a horizon 15 cm or more thick with 12 cmol(-)/L nitrate in 1:5 soil/water extract and in

Fig. 4. The Pleistocene site in the Salar de Llamara, a dried lake. The surface is now covered in a rough and indurated halite crust formed through prolonged hyperaridity and evaporative loss of the water table.

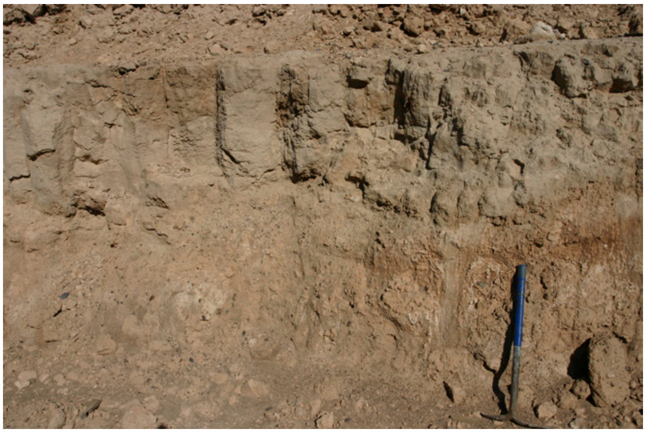

Fig. 5. An example of a soil profile from a well-drained alluvial fan in the Atacama Desert. Large sulfate polygons are present at the surface overlying a nitrate rich horizon and an indurated salic horizon deeper in the profile.

which the product of its thickness (in cm) and its nitrate concentration is ≥3500.

This is the current criteria used to designate a Nitric Anhyorthel in soil taxonomy (Soil Survey Staff, 1999), and the same definition suggested for a nitric horizon by the International Committee on Permafrost Affected Soils (Bockheim, 1997). For a soil with a bulk density of 1.5 g cm^{-3} this is equivalent to 2.5% nitrate.

To accommodate these new diagnostic subsurface horizons we also propose the addition of a Petrosalids great group

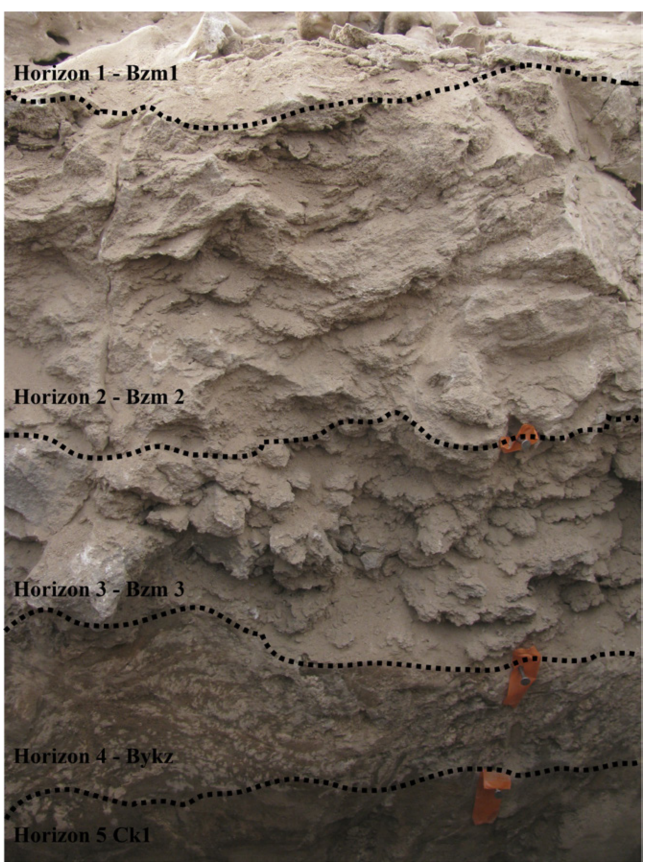

Fig. 6. Soil profile from the Pleistocene site in the Salar de Llamara. The first three horizons (0–51 cm) are hard, dense halite crust. These overlay a sulfate-rich horizon at 51 to 65 cm.

in the suborder Salids, and five subgroups to the new Petrosalids great group (Epi Petrosalids, Petrogypsic Petrosalids, Gypsic Petrosalids, Nitric Petrosalids, and Typic Petrosalids). We suggest that the new key for the Salids be as follows:

SALIDS
Key to Great Groups

GBA. Salids that are saturated with water in one or more layers within 100 cm of the mineral soil surface for 1 mo or more in normal years.

Aquisalids

GBB. Salids that have a petrosalic horizon within 200 cm of the soil surface.

Petrosalids

GBC. Other Salids.

Haplosalids

Petrosalids
Key to Subgroup

GBBA. Petrosalids that have a petrosalic horizon at the soil surface.

Epi Petrosalids

GBBB. Petrosalids that have a petrogypsic horizon within 100 cm of the soil surface.

Petrogypsic Petrosalids

GBBC. Petrosalids that have a gypsic horizon within 100 cm of the soil surface.

Gypsic Petrosalids

GBBD. Petrosalids that contain a horizon 15 cm or more thick with 12 cmol(-)/L nitrate in 1:5 soil/water extract and in which the product of its thickness (in cm) and its nitrate concentration is ≥3500.

Nitric Petrosalids

GBBE. Other Petrosalids.

Typic Petrosalids

Hyperaridic Soil Moisture Regime

Finally, we suggest that a fundamental way to distinguish pedogenesis in hyperarid climates is lacking. The creation of a Hyperaridic SMR would provide a critical means to distinguish between pedogenesis occurring in arid and hyperarid environments. This SMR should consider soils that experience rainfall averages incapable of removing soluble salts from the upper 150 cm over long time scales, therefore allowing the formation of indurated horizons. Such a revision to the soil taxonomy would require an international effort to arrive at an appropriate definition and classification system, however it would greatly enhance the usefulness of the Soil Taxonomy. To limit the need for major revisions to Aridisols, we suggest that the Hyperaridic SMR could be indicated at the family level (e.g., coarse-gypseous, isothermic, shallow, hyperaridic Typic Petrogypsid).

Impact of Proposed Changes

With these proposed changes the well-drained, post-Miocene soils in the Atacama Desert would change from their current designation as Petrogypsic Haplosalids to Petrogypsic Petrosalids, and the salar soils would change from their present designation as Gypsic Haplosalids to Epi Petrosalids. Additionally, all of the indurated salic horizons described in Table 1 would be classified as petrosalic horizons and the horizons enriched with nitrate classified as nitric horizons. Changes to the classification of these soils would vary depending on other individual factors of the soil, however many of them would change at the Great Group and/or Subgroup level to incorporate the new additions proposed here. These changes would also facilitate a more accurate description of future soil surveys and analysis in other hyperarid locations.

CONCLUSIONS

As new research is compiled, it is becoming clear that soils of hyperarid regions have unique features and processes not occurring in the more humid deserts. Horizons present in hyperarid regions are not included as diagnostic horizons in the soil taxonomy and as a result these soils are not adequately identified by the current Aridisols architecture. We propose that the soil taxonomy be amended to include a petrosalic diagnostic subsurface horizon, nitric diagnostic subsurface horizon, and a Petrosalids great group within the Aridisols order. Additionally, future research to define a new Hyperaridic SMR should be considered. The goal of this paper is to present the pedological characteristics of hyperarid soils to a broad audience and begin a larger discussion of possible changes to the soil taxonomy. The changes proposed here would create a more encompassing classification system.

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