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Distribution and properties of soft weathered bedrock at ≤ 1 m depth in the contiguous United States

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ABSTRACT: The weathered bedrock zone is increasingly recognized as an important part of ecological and hydrologic systems, but its distribution is poorly known in the contiguous United States. We used spatial and laboratory characterization data from the US Department of Agriculture (USDA)-Natural Resources Conservation Service to assess the distribution and soil-like properties of soft weathered bedrock (saprock and saprolite) within the 48 contiguous United States. Because USDA soil inventories generally do not extend below 2 m, and because the upper 1 m is clearly involved in ecosystem function and vadose zone hydrology, we restricted our inquiry to soft weathered bedrock within 1 m of the land surface. Soft weathered bedrock within 1 m of the land surface is widespread throughout the contiguous United States, underlying at least 6% of the land area. In-depth analysis of three states showed that soft weathered bedrock at the ≤ 1-m depth underlies 22% of the total land area in California, 33% in Wyoming, and 18% in North Carolina. Soft weathered bedrock hosts pedogenic activity, as indicated by morphological features such as roots, clay films, and iron (Fe)-/manganese (Mn)-oxide concretions recorded in pedon descriptions in the database. The physical and chemical properties of soft weathered bedrock are often similar to those of the overlying soil, suggesting that in many respects soft weathered bedrock behaves like soil. It supplies water and nutrients to plants whose roots penetrate into it and it modulates throughflow runoff to streams. For a more complete understanding of soft weathered bedrock, systematic data are needed on its thickness across landscapes and a consistent terminology for its various forms needs to be adopted and widely used. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: regolith; weathering; soil; bedrock; saprolite

Introduction

In upland regions, soils are often underlain by weathered bedrock. The weathered bedrock zone, below the soil and above unweathered bedrock, is increasingly being recognized as a critical component of ecosystems (e.g. Graham *et al.*, 2010), weathering reactions (e.g. Minyard *et al.*, 2011), landscape evolution (e.g. Dixon *et al.*, 2009a), and watershed hydrology (e.g. Bales *et al.*, 2011). Weathered bedrock has been altered from its original state by chemical weathering processes, such as oxidation of iron (Fe)-bearing minerals and hydrolysis of feldspars, but its original rock fabric is preserved even as bulk density and mechanical strength decrease. Porosity production during weathering converts hard and essentially impervious rock into a regolith that has soil-like properties (Navarre-Sitchler *et al.*, 2010; Rossi and Graham, 2010) and assumes important hydrologic, ecosystem, and biogeochemical functions in the environment.

For more than a century, the US Geological Survey has generated maps of bedrock geology and the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS; formerly Soil Conservation Service) has produced maps that identify the type, distribution, and properties of soils across landscapes. Unfortunately, the interface between unweathered bedrock and soil has been largely neglected, and no systematic inventory or assessment of weathered bedrock exists. Correspondingly, while well-defined terms exist for rocks (e.g. Ehlers and Blatt, 1982; Bates and Jackson, 1984) and soil (e.g. Soil Science Glossary Terms Committee, 2008; Soil Survey Staff, 2010), the nomenclature for the transitional weathered bedrock zone is less well-known, not consistently applied, and insufficient to identify important differences. Relevant terms and their definitions as used in this paper are compiled in Table I, but more terms will be needed as our knowledge of weathered bedrock grows and is refined.

Simple ranking systems can be used to identify the degree of bedrock weathering (e.g. Clayton and Arnold, 1972), but of key importance is the development of sufficient porosity such that the material effectively stores and conducts water. This amount of porosity generally corresponds with loss of mechanical

Table I. Terms for weathered bedrock and related materials. Definitions derived from the sources indicated

Term	Definition (reference)
Unweathered bedrock	Solid rock, unaltered by chemical or physical weathering, exposed at the surface or overlain by regolith. It is continuous laterally and vertically (thereby excluding boulders) (Bates and Jackson, 1984).
Weathered bedrock	Bedrock that is altered from its original state by chemical weathering processes (e.g. oxidation, hydrolysis). Various classes have been recognized (e.g. Clayton and Arnold, 1972), ranging from hard, with minimal alteration, to soft. Soft weathered bedrock, such as saprock or saprolite, can be crumbled by hand (equivalent to Cr horizon material).
Grus	An accumulation of loose, angular, coarse-grained fragments resulting from the granular disintegration of crystalline rocks, especially granitic rocks (Bates and Jackson, 1984).
Saprock	Weathered rock that retains the original rock fabric, but crumbles by hand to individual grains (i.e. crumbles to grus). Mineral grains are not extensively chemically altered and clay mineral content is minimal (Anand and Paine, 2002; Graham *et al.*, 2010).
Saprolite	Highly weathered rock that retains the original rock fabric, but most weatherable minerals are altered to clay minerals. It is easily crumbled by hand (i.e. it is friable) and becomes plastic when wet (Anand and Paine, 2002; Graham *et al.*, 2010).
Soil	A natural body of granular solids (comminuted rock materials and organic matter), liquids, and gases that occurs on the land surface and has horizons distinguishable from the initial material as a result of additions, losses, transfers, and transformations. Has the ability to support rooted plants in the natural environment (Soil Survey Staff, 2010).
Regolith	All incoherent earth material above hard bedrock; includes soil, saprolite, saprock, loess, colluvium, alluvium, tephra, and other unconsolidated sediments (Bates and Jackson, 1984).
R horizon	A soil morphologic horizon designation indicating bedrock that is sufficiently coherent when moist to make hand digging impractical. Cannot be broken in one's hands (Soil Survey Staff, 2010).
Cr horizon	A soil morphologic horizon designation indicating bedrock that is sufficiently weathered or otherwise soft such that it requires no more than moderate force to be broken between one's hands (Soil Survey Staff, 2010).
Paralithic material	Partially weathered or weakly consolidated bedrock that requires no more than moderate force to be broken between one's hands. Roots can penetrate only through cracks, not through the matrix (Soil Survey Staff, 2010).
Lithic contact	The boundary between soil and underlying bedrock that is sufficiently coherent when moist to make hand digging impractical. Cracks that can be penetrated by roots must be $>$ 10 cm apart (Soil Survey Staff, 2010).

strength so that the rock becomes soft and friable (saprock and saprolite); that is, it can be crumbled in one's bare hands (e.g. Jones and Graham, 1993).

Recognizing that soft weathered bedrock is important to ecosystems, hydrology, and environmental quality, this research was designed to evaluate it on a broader scale than it is generally considered. Our objectives were to (i) to determine the regional distribution, lithology, and soil-like properties of soft weathered bedrock within the contiguous United States, (ii) to compare these properties to those of the overlying soil, (iii) to examine the relevance of weathered bedrock properties to pedological, ecological, and hydrological functions, and (iv) to assess needs relative to improved inventory and understanding of soft weathered bedrock.

Materials and Methods

Spatial data on soils and bedrock were obtained from the NRCS database known as STATSGO, which is designed for regional assessments of soil resources. This database provides national coverage at a scale of 1:250 000 and was compiled by generalizing detailed, county-level soil survey maps. At the time the STATSGO database was compiled, detailed mapping was completed for virtually all the eastern and midwestern states, while parts of some of the western states remained unmapped. For these areas where detailed soil mapping was not available, other environmental data were used to interpret soil occurrence for STATSGO (Soil Survey Staff, 1995). A second database, SSURGO, is compiled entirely from detailed soil mapping but we did not use it because it was not complete for all regions.

STATSGO data were analyzed using Arc View (ESRI, 1999; Wald, 2001). The spatial data identify soil series in map units and each map unit is linked to tables containing general information, including characteristics of special interest to this study – depth to bedrock and whether the bedrock is hard or soft. Hard bedrock equates to the NRCS definition of 'R horizon'; soft bedrock equates to 'Cr horizon' and includes saprock and saprolite (Table I). In this study, then, 'soft weathered bedrock' is used to refer to this 'soft bedrock', Cr horizon material (i.e. saprock and saprolite). Bedrock lithology was determined from soil series descriptions in the NRCS Official Series Database (OSD).

Regional distributions

During the course of USDA soil surveys, soils are investigated to the 2 m depth or hard bedrock, whichever is encountered first (Wysocki *et al.*, 2005; Soil Survey Staff, 2010). Therefore, soil survey data can at best inform us about soft weathered bedrock within the upper 2 m. Deeper saprock and saprolite, while important, cannot be assessed from existing soil survey data. With STATSGO we further limited the inventory to the occurrence of soft weathered bedrock within 1 m of the surface because at this depth it is clearly involved in ecosystem function and vadose zone hydrology (Graham *et al.*, 1994; Graham *et al.*, 2010). With this in mind, it should be recognized that soft weathered bedrock, inclusive of its deeper occurrences, is far more extensive than our maps depict. Our assessment of regional distribution also used the criterion that the soft weathered bedrock at the $\leq$ 1 m depth must be present throughout at least 50% of the map unit.

An inherent limitation of STATSGO and the OSD with regard to the mapping and interpretation of soft weathered bedrock is that the manner in which it was designated was not entirely consistent among states. For example, certain soft weathered bedrock (saprock) may be described as an R layer instead of a Cr horizon, or, particularly in the case of saprolite, may be described as a C or even B horizon. Because the STATSGO data are compiled by generalizing the county soil survey data on a state-by-state basis, soft weathered bedrock may be underestimated in a state if it was not identified as Cr horizon.

To assess soft weathered bedrock distribution and properties by lithology, we limited that part of the study to three states, each with a dominant lithology: California with granitic rock, Wyoming with shale and sandstone, and North Carolina with saprolitic gneiss and schist. The rock types in each state were displayed based on the dominant lithology of each map unit. For example, if a map unit had 20% sandstone, 25% gneiss, and 45% granitic rock, it would be displayed as having granitic lithology. In some parts of the country, including North Carolina, saprolite has not been designated as Cr horizon, thus it is not ranked in STATSGO as 'soft bedrock'. Identifying soft weathered bedrock for North Carolina required the additional step of individually checking the soil series in the STATSGO database to determine the presence of soft weathered bedrock, including saprolite.

Morphological, physical, and chemical properties

Physical and chemical properties of soil and underlying soft weathered bedrock derived from granitic, shale, sandstone, gneiss, and schist parent rock were generated by the National Soil Survey Laboratory (NSSL) (Soil Survey Staff, 1997). As is standard for soil survey analyses, they are for the fine earth (< 2 mm diameter) fraction, which was obtained by gentle crushing and sieving of the material. All morphological, physical, and chemical data reported were determined using standard soil survey field and laboratory methods (Soil Survey Staff, 1993, 1996). These data are from pedons with specific weathered bedrock lithologies as indicated. The data were not limited to the three states for which the distribution of soft weathered bedrock was examined by lithology, rather they were drawn from the national data pool for soil series identified by STATSGO as having soft weathered bedrock within 1 m of the surface. In most cases, the soft weathered bedrock is designated as 'Cr hoizon', but in some soil series saprolite is designated as simply 'C horizon'. As noted previously, those series were identified by studying official series descriptions and the relevant characterization data (Soil Survey Staff, 1997) were obtained for them as well. Lithologic identities of the soft weathered bedrock were obtained from the official soil series descriptions. The categories of 'saprolitic gneiss' and 'saprolitic schist' were distinguished for those soil series, mapped in the south-eastern United States, in which saprolite was noted in their official descriptions.

Results

Distribution of weathered bedrock in the contiguous United States

Overall, soft weathered bedrock within 1 m of the surface underlies at least 6% of the land area of the contiguous United States. Much of it occurs in the form of soft sedimentary rock (shale, sandstone, siltstone) in the upper western portion of the Great Plains Province, covering the eastern half of Montana, north-eastern Wyoming, south-western North Dakota, and the western half of South Dakota (Figure 1). Within that region there is an area coinciding with the Black Hills that is shown to lack soft weathered bedrock within 1 m of the surface. Another major soft weathered bedrock body is the soft sedimentary rock that occurs in south-western Wyoming and stops abruptly at the Utah border. This abruptness is suggestive of an artifact from mismatched map databases rather than a natural difference in regolith.

A large extent of soft weathered bedrock within 1 m of the surface occurs in the eastern third of the United States. Soft weathered bedrock in that region follows the general shape of the Appalachian Mountains, spanning from north-eastern Georgia up into Pennsylvania, underlying parts of Tennessee, North Carolina, Virginia, and Maryland. Much of the bedrock in this region consists of igneous and metamorphic rocks. Other major areas of soft weathered sedimentary bedrock are found in northern Kentucky, in the Blue Grass Region, and in southern Indiana. In West Virginia, most soft weathered bedrock (≤ 1 m deep) occurs in the sedimentary terrain of the Appalachian Plateau Province, as does the soft weathered bedrock in western Pennsylvania and southern Ohio.

In California, soft weathered granitic bedrock (≤ 1 m deep) is prevalent in the Sierra Nevada Mountains, mainly on the western slopes of the range, and in the Peninsular Ranges, covering extensive areas in the south-western part of the state. Soft weathered bedrock of various lithologies underlies parts of the Coastal Ranges in California and Oregon and the western portion of the Basin and Range Province, covering areas in eastern California and central Nevada. The Colorado Plateau, which includes parts of Utah, Arizona, Colorado, and New Mexico, contains soft weathered sedimentary bedrock. Soft weathered

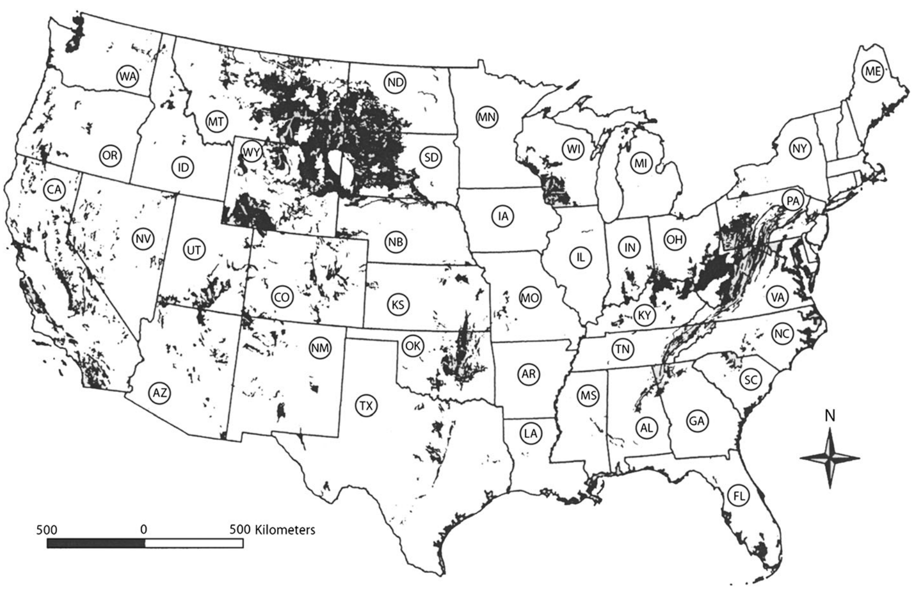

Figure 1. Distribution of soft weathered bedrock in the contiguous United States as generated by STATSGO using the criteria: (1) ≥ 50% polygon coverage and (2) soft weathered bedrock encountered at ≤ 1 m from the surface. State name abbreviations are presented in circles.

sedimentary bedrock also occurs in southern Florida, south-western Wisconsin, and a zone running from east central Texas northward through Oklahoma and into south-eastern Kansas.

Areas devoid, or containing minimal areas, of soft weathered bedrock within 1 m of the surface include the New England Province states, New York, Michigan, Minnesota, Iowa, Illinois, Arkansas, and Louisiana.

Weathered bedrock lithology and distribution in California

Soft weathered bedrock (at ≤ 1 m depth, ≥ 50% of map unit) underlies 22% of the land area in California (Figure 2). Soft weathered granitic rock (Figure 3) dominates, covering 9% of the land area, and is widespread throughout much of the state, occurring in the Sierra Nevada, Coastal, Transverse, and Peninsular Mountain Ranges, as well as the Basin and Range Province.

The area and percent of the major types of soft weathered bedrock in California are shown in Table II. Granitic bedrock comprises 43% of the total area of soft weathered rock and sedimentary rocks make up 32%, of which 12% is sandstone and 14% is shale. Weathered volcanic bedrocks make up about 6% of the total and weathered metamorphic bedrocks make up about 5%.

Soft weathered sedimentary bedrock is dominant in the Coast Ranges, but occurs in small amounts in other parts of the state (Figure 2). Soft weathered metamorphic bedrock is dominant on the eastern side of the Peninsular Range, but also occurs in the Sierra Nevada Range and in the Basin and Range Province.

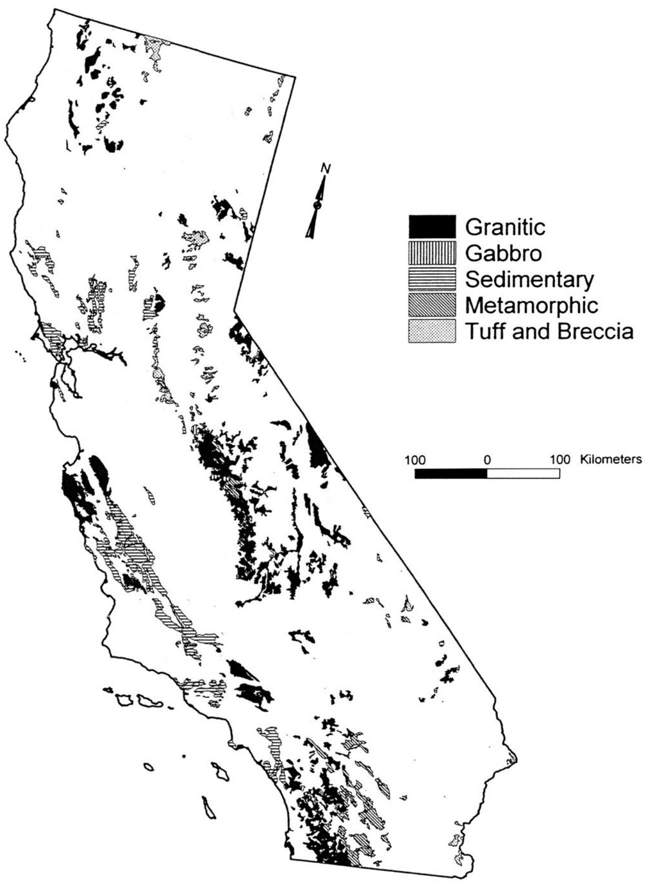

Figure 2. Distribution of soft weathered bedrock in California as generated by STATSGO using the criteria: (1) ≥ 50% polygon coverage, (2) soft weathered bedrock encountered at ≤ 1 m from the surface, and (3) bedrock type indicated is the dominant type in the map unit.

Figure 3. Granitic saprock in the San Jacinto Mountains in southern California. Note roots protruding from joint fractures. Rock matrix can be easily excavated with hand pick, knife, or spade, but individual minerals show little sign of chemical alteration. Exposed section is about 5 m thick; man in photograph is 1·85 m tall.

Soft weathered volcanic bedrock is predominantly found in northern California, in the Cascade-Sierra Nevada Ranges, but is also in scattered areas of the Basin and Range Province in south-eastern California.

Weathered bedrock lithology and distribution in Wyoming

Soft weathered bedrock (≤ 1 m deep) underlies 33% of the land area in Wyoming (Figure 4). Of this, the dominant lithology is sedimentary (Figure 5; Table III), accounting for 85% of the total soft weathered bedrock (≤ 1 m deep) area. The type of soft sedimentary bedrock is further identified as shale and stratified sedimentary rock (26% each), sandstone (19%), and siltstone (7%).

Soft weathered bedrock (≤ 1 m deep) is found predominately in the basins of Wyoming. In the Green River, Great Divide, and Washakie Basins of the south-western part of the state,

Table II. Percent and area of major soft weathered bedrock types in California as determined using STATSGO and OSD data

Type of rock	Percentage of total	Land area (hectares)
Igneous		
Granitic	42·9	456 366
Gabbro	5·3	56 381
Andesite	0·3	3191
Tuff/Breccia	6·0	63 827
Sedimentary		
Sandstone	12·4	131 910
Shale	13·8	146 803
Conglomerate	2·5	26 595
Miscellaneous	4·4	46 807
Metamorphic	4·6	48 934
Other areas with soft weathered bedrock		
Badland	3·6	38 296
Urbanland	0·4	4255
Rock outcrop	1·6	17 021
DNE [a]	2·2	23 403
Total	100	1 063 790

[a]DNE = does not exist, some map unit components (soil series) were not found in any database other than STATSGO.

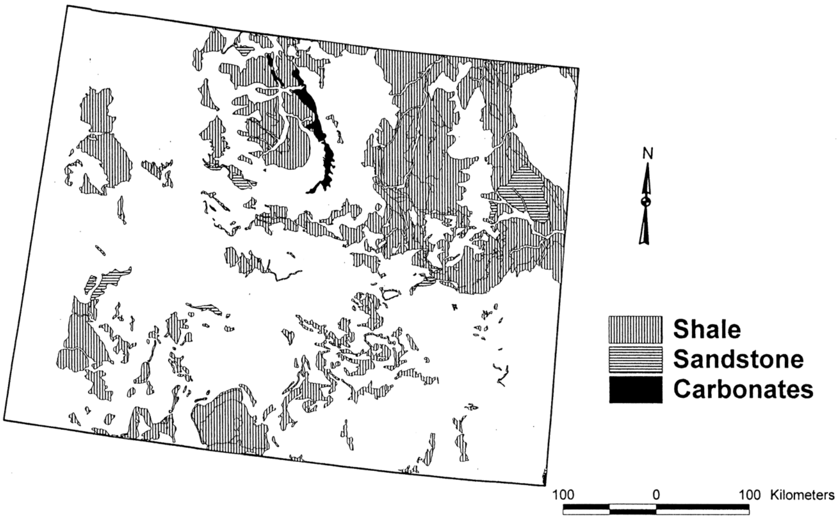

Figure 4. Distribution of soft weathered bedrock in Wyoming as generated by STATSGO using the criteria: (1) ≥ 50% polygon coverage, (2) soft weathered bedrock encountered at ≤ 1 m from the surface, and (3) bedrock type indicated is the dominant type in the map unit.

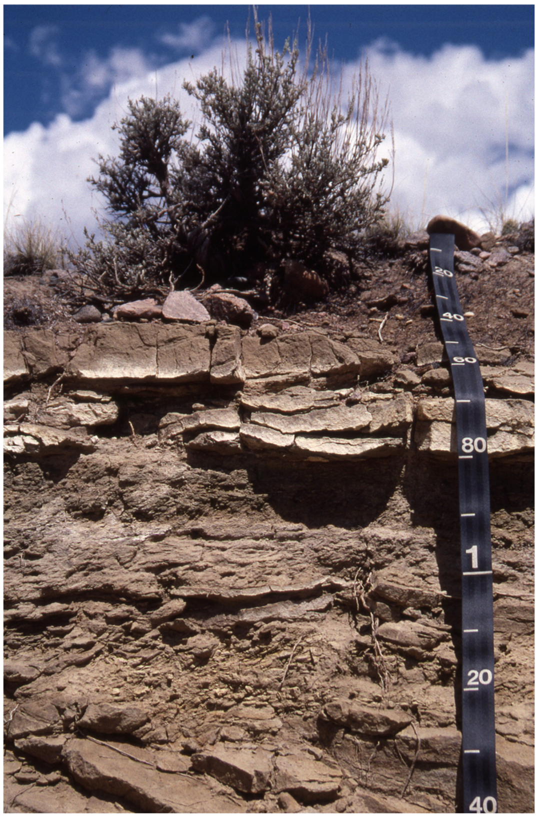

Figure 5. Soft, weathered sedimentary bedrock in southeastern Wyoming. Note interbedded strata with different resistance to weathering, and roots that penetrate through cracks in the strata. Scale marked in 10 cm increments.

Table III. Percent and acreage of major soft weathered bedrock types in Wyoming as determined using STATSGO and OSD data

Type of rock	Percentage of total	Land area (hectares)
Sedimentary		
Sandstone	18·7	1 055 097
Siltstone	6·7	384 559
Shale	25·9	1 486 580
Stratified	26·0	1 492 319
Sedimentary beds	3·5	200 889
Limestone	1·9	109 054
Gypsum	1·0	57 397
Other areas with soft weathered bedrock		
Rock outcrop	10·7	614 147
Badland	1·1	63 137
Ustic Torriorthents	< 0·1	< 1
DNE[a]	4·5	258 286
Total	100	5 721 465

[a]DNE = does not exist, some map unit components (soil series) were not found in any database other than STATSGO.

weathered shale bedrock dominates but there are smaller areas of weathered sandstone. In the northern central part of the state, shale is also the dominant lithology, but smaller areas of sandstone and carbonates are found as well. In north-eastern Wyoming, in the Powder River Basin, shale is the most common lithology of soft weathered bedrock (≤ 1 m deep) with one smaller area dominated by sandstone. Areas shown to be lacking soft weathered bedrock within 1 m of the surface coincide with the mountain ranges, such as the Bighorn, Beartooth, Teton, Laramie, Wind River, Owl Creek, and Medicine Bow Mountains. The Black Hills, Sweetwater Uplift, and Cheyenne Basin are also not underlain by soft weathered bedrock according to the display criteria of this study.

Weathered bedrock lithology and distribution in North Carolina

Soft weathered bedrock within 1 m of the surface underlies 18% of the land area in North Carolina (Figure 6), and 45% of this (11% of the land area) is weathered gneiss and schist (Figure 7; Table IV). Also included are significant areas of intrusive igneous lithologies such as granite, diorite, and gabbro. In all, intrusive igneous, gneiss, and schist bedrock comprise 63% of the total soft weathered bedrock area. Metasedimentary rocks including slate, phyllite, and metasandstone comprise about 15% of the soft weathered bedrock area. Stratified metamorphic and igneous rocks comprise the remaining 22%.

Soft weathered bedrock (≤ 1 m deep) occurs in the Piedmont and Blue Ridge physiographic provinces, and is non-existent in the Coastal Plain province. Most of the saprolitic gneiss and schist meeting the criteria of this study is found in the Blue Ridge Province. Most of the other metamorphic rocks in the

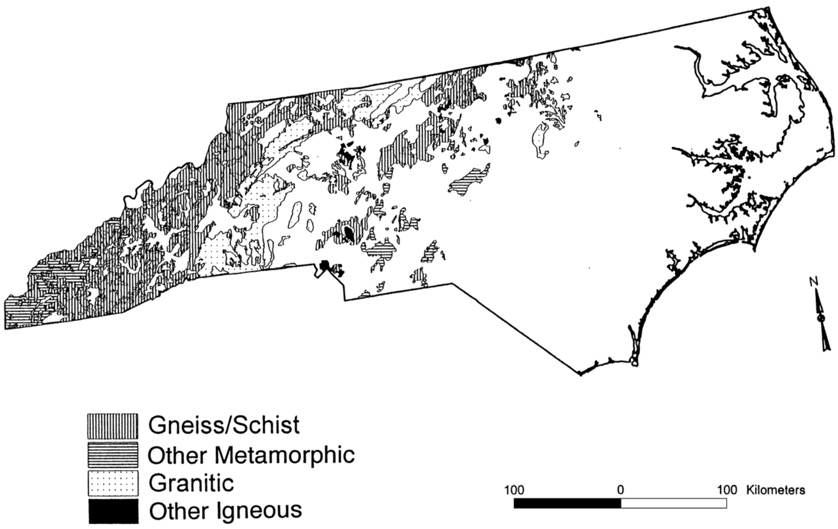

Figure 6. Distribution of soft weathered bedrock in North Carolina as generated by STATSGO using the criteria: (1) ≥ 50% polygon coverage, (2) soft weathered bedrock encountered at ≤ 1 m from the surface, and (3) bedrock type indicated is the dominant type in the map unit.

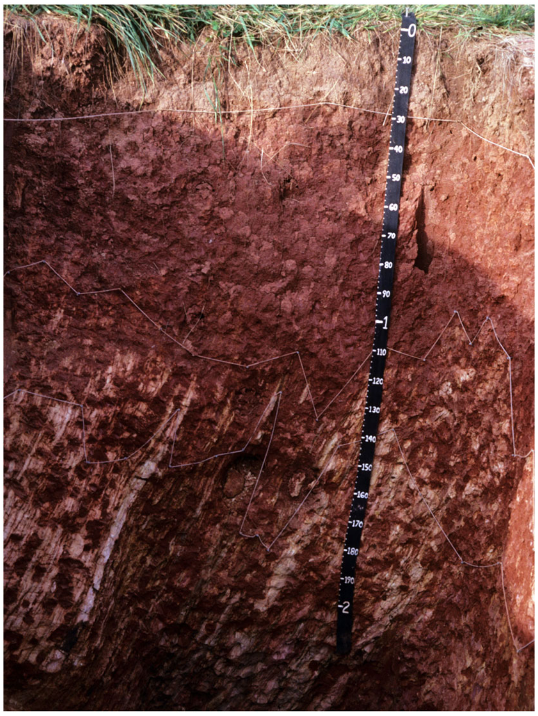

Figure 7. Felsic crystalline schist saprolite in the northeastern Piedmont of North Carolina. Note steeply dipping foliation of the intact schist bedrock (below 110 cm). The weatherable minerals in the bedrock have been thoroughly chemically weathered to clays and iron oxides, yielding a soft, easily excavated saprolite. Scale labeled in 10 cm increments to the 2-m depth.

Piedmont are within the Carolina Slate Belt. Soft weathered intrusive igneous bedrocks, such as granite, are also found in the Piedmont.

Morphological properties

While the thoroughness of morphologic descriptions varies, all types of soft weathered bedrock hosted roots, clay films, fractures and other macroscopic pores, and Fe- and manganese (Mn)-oxide stains and other mottles (Table V). Calcium carbonate and gypsum were only described in weathered sedimentary bedrock.

Table IV. Percent and acreage of major soft weathered bedrock types in North Carolina as determined using STATSGO and OSD data

Type of rock	Percentage of total	Land area (hectares)
Igneous		
Granitic	9·8	229 343
Diorite/Gabbro	7·8	238 252
Igneous/Metamorphic (stratified)	22·4	684 212
Metamorphic		
Schist	16·8	513 159
Gneiss	28·6	873 592
Slate	6·4	195 489
Phyllite	3·4	103 853
Metasandstone	4·7	143 562
Total	100	2 981 462

Physical properties

Mean values of physical properties were calculated using all available characterization data for granitic, shale, sandstone, gneiss, and schist soft weathered bedrock (Cr horizons), and their overlying soils, in the contiguous United States (Table VI).

The granitic Cr horizons average 81% sand, 12% silt, 7% clay, a textural class of loamy sand, and a fine clay/total clay (FC/TC) ratio of 0·50 g g^{-1}. Soft weathered sandstone, schist (both saprock and saprolite), and gneiss (both saprock and saprolite) all average sandy loam textures, but the saprolites have less sand than their saprock counterparts. The FC/TC ratio for soft weathered sandstone is 0·45. FC/TC ratios for saprock schist (0·63) and gneiss (0·34) are higher than for saprolite schist (0·34) and gneiss (0·27). Soft weathered shale averaged a silty clay loam texture (15% sand, 47% silt, 38% clay) and one of the lowest FC/TC ratios (0·30) of all the soft weathered bedrock types.

In general, the percentage of sand increases from the soil horizons down to the Cr horizons, with the exception of shale (Table VI). The B horizon has the highest clay percentage in regolith profiles of all bedrock types. FC/TC ratios increase with depth in the soils, except those derived from sandstone or shale, and are greater than in soft weathered bedrock, with the exception of granitic and schist bedrock.

Soil bulk densities increase with depth to Cr horizons, except in the case of saprolites (schist and gneiss), which have lower

Table V. The occurrence of selected morphological properties of soft weathered bedrock as given in pedon descriptions[a]

Rock type	Roots (%)	Clay films (%)	Fractures (%)	Pores (%)	Fe- or Mn-oxide concentrations (%)	Mottles (%)	Calcite (%)	Gypsum (%)
Schist (n = 27)	70	11	4	41	30	7	0	0
Gneiss (n = 26)	42	0	4	15	27	19	0	0
Granite (n = 23)	43	35	13	9	9	13	0	0
Sandstone (n = 67)	37	3	19	7	4	7	25	4
Shale (n = 74)	39	5	12	4	27	9	27	30

[a]Pedon descriptions are from the NSSL characterization database (Soil Survey Staff, 1997).

Table VI. Selected physical properties[a] of soft weathered bedrock and overlying soil. All values are for the fine-earth (< 2 mm diameter) fraction[b]

Realtive profile depth[c]	Sand (%)		Silt (%)		Clay (%)		Fine clay/total clay (g g^{-1})		Texture[d]	Bulk density (Mg m^{-3})[e]		WHC (cm cm^{-1})[f]	
	$x_{(n)}$	SE	$x_{(n)}$	SE	$x_{(n)}$	SE	$x_{(n)}$	SE		$x_{(n)}$	SE	$x_{(n)}$	SE
Granitic													
A	69·9$_{(43)}$	1·9	22·0$_{(43)}$	1·5	8·2$_{(43)}$	0·8	0·33$_{(13)}$	0·04	sl	1·50$_{(27)}$	0·05	0·13$_{(27)}$	0·01
B	68·6$_{(43)}$	2·4	17·3$_{(43)}$	1·1	14·0$_{(43)}$	2·1	0·44$_{(14)}$	0·04	sl	1·77$_{(28)}$	0·04	0·09$_{(29)}$	0·00
C	71·2$_{(43)}$	2·6	14·6$_{(43)}$	1·0	14·2$_{(43)}$	2·3	0·45$_{(14)}$	0·04	sl	1·79$_{(27)}$	0·05	0·09$_{(27)}$	0·01
Cr (saprock)	81·1$_{(43)}$	1·2	12·2$_{(43)}$	0·7	6·7$_{(43)}$	0·8	0·50$_{(12)}$	0·04	ls	2·04$_{(18)}$	0·08	0·08$_{(17)}$	0·01
Sandstone													
A	58·7$_{(68)}$	2·2	27·5$_{(68)}$	1·7	13·8$_{(68)}$	0·9	0·53$_{(29)}$	0·03	sl	1·44$_{(46)}$	0·02	0·11$_{(45)}$	0·01
B	53·0$_{(68)}$	2·3	26·2$_{(68)}$	1·7	21·0$_{(68)}$	1·4	0·51$_{(30)}$	0·04	scl	1·60$_{(48)}$	0·02	0·11$_{(45)}$	0·01
C	59·3$_{(68)}$	2·3	24·4$_{(68)}$	1·8	16·2$_{(68)}$	1·2	0·51$_{(29)}$	0·03	sl	1·61$_{(43)}$	0·03	0·11$_{(41)}$	0·01
Cr (saprock)	70·2$_{(68)}$	1·8	18·5$_{(68)}$	1·4	11·4$_{(68)}$	0·8	0·45$_{(25)}$	0·04	sl	1·68$_{(34)}$	0·03	0·12$_{(33)}$	0·01
Shale													
A	20·9$_{(105)}$	1·7	43·0$_{(105)}$	1·1	36·1$_{(105)}$	1·5	0·47$_{(43)}$	0·03	cl	1·51$_{(68)}$	0·02	0·14$_{(61)}$	0·01
B	14·9$_{(106)}$	1·4	40·5$_{(106)}$	1·0	44·8$_{(106)}$	1·5	0·43$_{(44)}$	0·03	sic	1·78$_{(76)}$	0·02	0·12$_{(74)}$	0·01
C	14·4$_{(106)}$	1·5	44·3$_{(106)}$	1·2	41·5$_{(106)}$	1·6	0·36$_{(40)}$	0·03	sicl	1·81$_{(64)}$	0·02	0·12$_{(62)}$	0·01
Cr (saprock)	14·5$_{(106)}$	1·4	47·1$_{(106)}$	1·2	38·2$_{(106)}$	1·6	0·30$_{(34)}$	0·02	sicl	1·91$_{(50)}$	0·03	0·10$_{(49)}$	0·01
Schist													
A	47·6$_{(14)}$	3·8	31·5$_{(14)}$	3·4	20·9$_{(14)}$	1·6	0·32$_{(8)}$	0·04	l	1·44$_{(11)}$	0·10	0·16$_{(11)}$	0·02
B	50·1$_{(14)}$	4·5	23·9$_{(14)}$	3·2	26·0$_{(14)}$	4·7	0·44$_{(7)}$	0·07	scl	1·56$_{(12)}$	0·07	0·15$_{(12)}$	0·01
C	63·6$_{(14)}$	4·2	22·3$_{(14)}$	3·3	14·0$_{(14)}$	2·5	0·45$_{(6)}$	0·10	sl	1·70$_{(11)}$	0·08	0·15$_{(11)}$	0·02
Cr (saprock)	74·7$_{(13)}$	3·6	19·0$_{(13)}$	3·4	6·3$_{(13)}$	1·4	0·63$_{(4)}$	0·10	sl	1·81$_{(10)}$	0·11	0·12$_{(9)}$	0·01
Saprolitic Schist													
A	43·5$_{(15)}$	2·8	35·3$_{(15)}$	2·1	21·2$_{(15)}$	1·8	0·31$_{(10)}$	0·05	l	1·33$_{(8)}$	0·12	0·19$_{(9)}$	0·02
B	44·0$_{(15)}$	3·9	27·6$_{(15)}$	2·7	28·4$_{(15)}$	3·4	0·39$_{(9)}$	0·03	cl	1·54$_{(10)}$	0·11	0·15$_{(11)}$	0·01
C	50·5$_{(15)}$	3·9	27·1$_{(15)}$	2·3	22·4$_{(15)}$	2·8	0·42$_{(7)}$	0·05	scl	1·49$_{(9)}$	0·12	0·17$_{(10)}$	0·01
Cr (saprolite)	62·2$_{(15)}$	3·8	24·9$_{(15)}$	2·6	12·9$_{(15)}$	1·9	0·34$_{(8)}$	0·06	sl	1·46$_{(9)}$	0·08	0·19$_{(10)}$	0·03
Gneiss													
A	56·2$_{(14)}$	3·9	29·6$_{(14)}$	2·3	14·9$_{(14)}$	1·6	0·22$_{(7)}$	0·05	sl	1·55$_{(10)}$	0·10	0·17$_{(10)}$	0·02
B	52·5$_{(15)}$	4·3	24·8$_{(15)}$	2·8	22·7$_{(15)}$	4·2	0·27$_{(7)}$	0·07	scl	1·50$_{(12)}$	0·14	0·14$_{(12)}$	0·02
C	61·7$_{(15)}$	2·8	21·0$_{(15)}$	2·5	17·3$_{(15)}$	2·4	0·42$_{(6)}$	0·12	sl	1·83$_{(12)}$	0·11	0·14$_{(12)}$	0·02
Cr (saprock)	75·8$_{(14)}$	3·4	16·7$_{(14)}$	2·9	7·5$_{(14)}$	1·3	0·34$_{(5)}$	0·12	sl	2·02$_{(9)}$	0·12	0·13$_{(7)}$	0·02
Saprolitic Gneiss													
A	46·9$_{(15)}$	2·7	33·5$_{(15)}$	2·1	19·5$_{(15)}$	1·4	0·29$_{(10)}$	0·04	l	1·33$_{(11)}$	0·12	0·19$_{(12)}$	0·03
B	51·1$_{(15)}$	3·6	27·5$_{(15)}$	1·8	21·4$_{(15)}$	3·2	0·32$_{(11)}$	0·06	scl	1·55$_{(11)}$	0·04	0·18$_{(13)}$	0·01
C	59·2$_{(15)}$	3·1	27·0$_{(15)}$	2·1	13·9$_{(15)}$	2·1	0·34$_{(10)}$	0·06	sl	1·54$_{(11)}$	0·05	0·18$_{(10)}$	0·01
Cr (saprolite)	67·3$_{(15)}$	2·6	24·3$_{(15)}$	2·0	8·3$_{(15)}$	1·3	0·27$_{(11)}$	0·05	sl	1·49$_{(10)}$	0·07	0·22$_{(10)}$	0·02

[a]Physical properties were totaled from NSSL characterization data (Soil Survey Staff, 1997).
[b]$x(n)$ = mean value (number of samples); SE = standard error.
[c]Positions in profile roughly equate to A, B, C horizons as indicated.
[d]sl = sandy loam, ls = loamy sand, scl = sandy clay loam, cl = clay loam, sic = silty clay, sicl = silty clay loam, l = loam.
[e]Oven-dry bulk density.
[f]WHC = water-holding capacity: water held between –33 and –1500 kPa pressure.

bulk densities than B and C horizons (Table VI). Soft weathered granitic bedrock has, on average, the highest bulk density (2·04 Mg m^{-3}), equating to a total porosity of 23%. Soft weathered sandstone has the lowest bulk density of the five weathered bedrock types, excluding saprolites, averaging 1·68 Mg m^{-3}, which equates to a porosity of 37%. In contrast, saprolite bulk densities for schist (1·46 Mg m^{-3}) and gneiss (1·49 Mg m^{-3}) are much lower, reflecting higher porosities (45% for schist and 44% for gneiss).

Water retention difference between –33 and –1500 kPa approximates plant-available water-holding capacity (WHC) and is expressed as centimeters of water held per centimeters of regolith. Granitic saprock has the lowest WHC at 0·08 cm cm^{-1} (Table VI). Soft weathered shale has a WHC of 0·10 cm cm^{-1}. Saprock sandstone, schist, and gneiss have WHC values of 0·12 to 0·13 cm cm^{-1}. The saprolites have much higher WHC, with 0·19 cm cm^{-1} for schist and 0·22 cm cm^{-1} for gneiss. In general, WHC values for soft weathered bedrock are somewhat lower

Table VII. Selected chemical properties[a] of soft weathered bedrock and overlying soil. All values are for the fine earth (<2 mm) fraction[b]

Relative profile depth[c]	pH 1:1		OC (%)[d]		CEC ($cmol_c\ kg^{-1}_{soil}$)[e]		Base sat. (%)[f]
	$x_{(n)}$	SE	$x_{(n)}$	SE	$x_{(n)}$	SE	
Granitic							
A	$5{\cdot}9_{(43)}$	0·1	$2{\cdot}79_{(43)}$	0·42	$11{\cdot}8_{(43)}$	1·5	76
B	$6{\cdot}0_{(43)}$	0·1	$0{\cdot}46_{(42)}$	0·05	$8{\cdot}5_{(43)}$	0·8	73
C	$6{\cdot}1_{(43)}$	0·1	$0{\cdot}29_{(42)}$	0·03	$8{\cdot}1_{(43)}$	0·7	75
Cr (saprock)	$6{\cdot}1_{(43)}$	0·1	$0{\cdot}13_{(42)}$	0·02	$6{\cdot}4_{(43)}$	0·6	88
Sandstone							
A	$6{\cdot}6_{(67)}$	0·1	$1{\cdot}40_{(68)}$	0·12	$12{\cdot}8_{(68)}$	0·8	100
B	$7{\cdot}1_{(67)}$	0·2	$0{\cdot}58_{(68)}$	0·07	$14{\cdot}6_{(68)}$	0·8	100
C	$7{\cdot}2_{(67)}$	0·2	$0{\cdot}37_{(68)}$	0·07	$12{\cdot}2_{(68)}$	0·7	100
Cr (saprock)	$7{\cdot}5_{(67)}$	0·2	$0{\cdot}15_{(67)}$	0·02	$9{\cdot}5_{(67)}$	0·8	100
Shale							
A	$7{\cdot}0_{(100)}$	0·1	$2{\cdot}42_{(104)}$	0·29	$26{\cdot}3_{(104)}$	1·2	100
B	$7{\cdot}4_{(101)}$	0·1	$0{\cdot}79_{(105)}$	0·06	$27{\cdot}7_{(105)}$	1·3	100
C	$7{\cdot}4_{(101)}$	0·1	$0{\cdot}50_{(105)}$	0·05	$25{\cdot}9_{(105)}$	1·3	100
Cr (saprock)	$7{\cdot}4_{(101)}$	0·1	$0{\cdot}29_{(105)}$	0·03	$24{\cdot}7_{(105)}$	1·3	100
Schist							
A	$5{\cdot}4_{(14)}$	0·2	$3{\cdot}61_{(14)}$	0·63	$16{\cdot}5_{(14)}$	2·5	37
B	$5{\cdot}6_{(14)}$	0·2	$0{\cdot}59_{(14)}$	0·24	$11{\cdot}9_{(14)}$	2·4	56
C	$5{\cdot}5_{(14)}$	0·2	$0{\cdot}31_{(14)}$	0·17	$9{\cdot}6_{(14)}$	1·7	50
Cr (saprock)	$5{\cdot}7_{(12)}$	0·2	$0{\cdot}09_{(13)}$	0·03	$6{\cdot}6_{(13)}$	1·2	56
Saprolitic Schist							
A	$5{\cdot}2_{(14)}$	0·2	$2{\cdot}83_{(15)}$	0·52	$14{\cdot}0_{(13)}$	2·2	43
B	$5{\cdot}3_{(14)}$	0·2	$0{\cdot}31_{(15)}$	0·05	$10{\cdot}1_{(13)}$	1·2	33
C	$5{\cdot}2_{(14)}$	0·1	$0{\cdot}15_{(15)}$	0·02	$8{\cdot}7_{(13)}$	1·0	30
Cr (saprolite)	$5{\cdot}1_{(14)}$	0·1	$0{\cdot}09_{(15)}$	0·02	$8{\cdot}5_{(13)}$	1·4	26
Gneiss							
A	$5{\cdot}3_{(14)}$	0·2	$3{\cdot}22_{(14)}$	0·99	$16{\cdot}1_{(14)}$	3·0	51
B	$5{\cdot}5_{(15)}$	0·2	$0{\cdot}88_{(15)}$	0·32	$14{\cdot}0_{(15)}$	2·3	59
C	$5{\cdot}8_{(15)}$	0·2	$0{\cdot}33_{(15)}$	0·10	$11{\cdot}6_{(15)}$	1·7	65
Cr (saprock)	$6{\cdot}0_{(14)}$	0·3	$0{\cdot}10_{(14)}$	0·04	$8{\cdot}1_{(14)}$	1·2	78
Saprolitic Gneiss							
A	$4{\cdot}8_{(15)}$	0·2	$4{\cdot}89_{(15)}$	1·10	$19{\cdot}6_{(15)}$	3·9	17
B	$5{\cdot}1_{(15)}$	0·1	$0{\cdot}42_{(15)}$	0·11	$8{\cdot}9_{(15)}$	1·0	20
C	$5{\cdot}0_{(15)}$	0·1	$0{\cdot}20_{(15)}$	0·05	$6{\cdot}9_{(15)}$	1·0	14
Cr (saprolite)	$5{\cdot}0_{(15)}$	0·1	$0{\cdot}26_{(15)}$	0·11	$6{\cdot}2_{(15)}$	0·8	15

[a]Chemical properties were totaled from NSSL characterization data (Soil Survey Staff, 1997).
[b]$x(n)$ = mean value (number of samples); SE = standard error.
[c]Positions in profile roughly equate to A, B, C horizons as indicated.
[d]OC = organic carbon.
[e]CEC = cation exchange capacity determined at pH 7.
[f]Base Sat. = base saturation determined at pH 7, (sum of exchangeable Ca, Mg, K, Na/CEC) × 100.

than those of the overlying soil horizons, with the exception of sandstone and the saprolites.

Chemical properties

For all regolith profiles except saprolitic schist, pH is highest in the soft weathered bedrock, generally increasing with depth from the A horizon (Table VII). Both soil and soft weathered bedrock of pedons with gneiss and schist saprolite are very strongly to strongly acid (pH is 4·8 to 5·3), whereas the pedons with saprock for the same rock types are strongly to moderately acid (pH is 5·3 to 6·0). Regolith profiles derived from granitic bedrock have a narrow range of pH values for all depths and are moderately to slightly acid. In contrast, pH values for both sedimentary rock types range from neutral to slightly alkaline (6·6–7·5).

Organic carbon (OC) decreases with depth for all bedrock types (Table VII). The A horizons of all regolith types have roughly similar OC values (2·4 to 4·9%) when the standard error is taken into consideration, except for those on sandstone, which average 1·4%. Soft weathered bedrock horizons of schist have the lowest OC content (0·09%), those of granitic, sandstone, and gneiss saprocks are somewhat higher (0·10–0·15%), while the highest are for weathered shale (0·26%) and saprolitic gneiss (0·29%).

The cation exchange capacity (CEC; capacity to retain exchangeable cations) decreases with increasing depth for all regolith profiles except sandstone and shale, in which CEC increases in the B horizon and then decreases with depth (Table VII). Shale saprock has the highest CEC (24·7 $cmol_c\ kg^{-1}_{soil}$), while sandstone saprock, gneiss saprock, and saprolitic schist have considerably lower values (8·1–9·5 $cmol_c\ kg^{-1}_{soil}$), and granitic saprock, schist saprock, and saprolitic gneiss have the lowest (6·2–6·6 $cmol_c\ kg^{-1}_{soil}$).

Base saturation [the percentage of the CEC occupied by calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na)] is highest in the sedimentary profiles, 100% throughout (Table VII). Otherwise, base saturation is higher in the saprocks (> 50%) than in overlying soil horizons, but in the saprolites base saturation is lower (26% for schist, 15% for gneiss) than in the overlying soils. Calcium is the most abundant base cation on exchange sites, with Mg second but considerably lower, for all soft weathered bedrocks except the saprolites (data not shown). In the saprolites, Ca and Mg are present in roughly equal proportions. Sodium and K are very low ($\leq$ 0·1 $cmol_c\ kg^{-1}_{soil}$) in all except the soft weathered sedimentary bedrocks (0·5–3·2 $cmol_c\ kg^{-1}_{soil}$).

Discussion

Controls on soft weathered bedrock distribution

Soft weathered bedrock is the dominant substratum underlying soil in widespread areas within the contiguous United States (Figure 1). But, as noted earlier, our maps greatly underrepresent the total area underlain by soft weathered bedrock because they only show the places where these materials occur within 1 m of the surface. By comparison, the map of surficial deposits of the United States prepared by Hunt (1989) shows the entire Piedmont region from eastern Pennsylvania through southern Alabama to be underlain by saprolite. More detailed mapping by Pavich *et al.* (1989) showed widespread occurrence of saprolite in Fairfax County, Virginia. Neither of these saprolite occurrences is fully depicted in Figure 1. Again, most of the saprolite in these areas occurs below the 1-m depth, so it is not represented in our maps.

The areas dominated by soft weathered bedrock in Figure 1 are in different climatic, ecological, and geological environments. Maps showing soft weathered bedrock of individual states (Figures 2, 4, and 6) demonstrate that it develops from a wide variety of rock types and that specific rock types (e.g. granite) can produce soft weathered bedrock under a wide range of climatic conditions (Figures 2 and 6). The properties of soft weathered bedrock of a given lithology, however, may vary considerably from a Mediterranean-type climate to a subtropical one (Pavich *et al.*, 1989; Graham *et al.*, 1997; Rasmussen *et al.*, 2011).

The distribution of soft weathered bedrock depends on the nature of the original bedrock, the temperature and moisture conditions, and the stability of the landscape. Other factors being equal, the thickness of soft weathered bedrock depends on the composition and structure of the rock. For example, on the Virginia Piedmont, felsic igneous rocks have thicker saprolite zones than mafic igneous rocks, and vertically foliated rocks have thicker saprolite than massive ones (Pavich, 1986; Pavich *et al.*, 1989). The weathering of even one susceptible mineral phase, such as biotite in granite, can generate substantial porosity and result in loss of mechanical strength, producing soft weathered bedrock (e.g. Isherwood and Street, 1976; Graham *et al.*, 2010). However, if all of the minerals in the rock are easily dissolved, no skeletal framework remains to produce soft weathered bedrock (Pavich *et al.*, 1989).

Rock weathering reactions increase with temperature and the amount of water flushing through the system (Dixon *et al.*, 2009a), so weathering profiles on long-stable landforms should be deepest in warm, humid climates. Within a landscape, topography affects the distribution of moisture such that convex landscape positions shed water while concave positions, especially lower on slopes, collect water (Graham, 2006). Thus, on hillslopes, bedrock weathering is generally deepest in concave positions and on lower slopes (e.g. Graham *et al.*, 1990; Ohnuki *et al.*, 1997). Nearly level upland positions neither shed nor collect water, rather infiltrating meteoric water has a strong vertical vector that can also result in deep weathering on these stable landscape positions (Pavich *et al.*, 1989; Stolt *et al.*, 1992). The amount of water reaching the soft weathered bedrock is further affected by the thickness and permeability of the overlying soil (Pavich, 1986), particularly on low gradient slopes that do not receive throughflow. Water within the soil is subject to storage and evapotranspirational losses, so thicker, less permeable soils result in less water reaching the underlying weathered bedrock zone.

The depth at which soft weathered bedrock occurs (i.e. the thickness of the soil mantle) is determined by the balance between erosion and the rate of conversion of the weathered bedrock to soil by processes of physical disruption, such as mixing by burrowing fauna (e.g. Dixon *et al.*, 2009b) and tree throw (e.g., Roering *et al.*, 2010). These bioturbation processes are most active in climates that support more biological activity (Dixon *et al.*, 2009b), but even there they become ineffective if the soil mantle thickens beyond the depths accessed by the biotic mixing agents (Heimsath *et al.*, 1999; Roering *et al.*, 2002). Thus, on stable landscape positions such as broad summits, the soil mantle achieves a certain equilibrium thickness that in effect protects the underlying soft weathered bedrock from further disruption because bioturbation processes cannot reach the soil-weathered bedrock interface. In these situations the soft weathered bedrock zone continues to thicken due to chemical weathering at its lower boundary even as the overlying soil mantle does not.

Tectonic or climatic influences can result in stream incision that in turn generates hillslope erosion. If the rate of erosion exceeds the rate of soil production, the thickness of the soil mantle over soft weathered bedrock is decreased (Heimsath *et al.*, 1999). So the depth at which soft weathered bedrock occurs is generally related to the balance between surface erosion and soil production. If erosion exceeds the rate of soft weathered rock formation, hard rock will eventually be exposed at the surface (Graham *et al.*, 2010). However, a high rate of erosion in some regions of sedimentary bedrock is irrelevant because the original bedrock itself is soft.

Explaining the site-specific controls for the regional distributions of soft weathered bedrock presented in this paper is beyond the scope of our study. Nevertheless, in a general sense, the broad patterns are governed by the same controls discussed earlier: the susceptibility of the rock itself to weathering, the temperature and amount of water available to effect weathering, the biological factors that promote mixing, and the stability of the landscape that allows for duration of weathering.

Pedogenic accumulations

Most of the soft weathered bedrock types have a coarse texture (loamy sand or sandy loam) (Table VI) because they are not so intensively weathered as the overlying soil horizons, where more of the weatherable minerals have been altered to clays. Weathered shale bedrock has a fine texture (silty clay loam) since shale itself is composed of mostly of silt- and clay-sized particles.

Several types of data support the concept that soil and bedrock are a continuum and that pedogenic processes bridge across these media in the zone of soft weathered bedrock. The accumulation of translocated clay (clay illuviation) is an important process in many soils (Turk *et al.*, 2012). Evidence of clay illuviation is found in the presence of oriented clay linings (clay films) and an increase in the fine:total clay (FC/TC) ratio relative to upper soil horizons. Clay linings in pores are produced by the intermittent and cumulative deposition of clay from suspension as the transporting water is absorbed into the surrounding matrix (Turk *et al.*, 2012). Because finer particles are preferentially transported, the FC/TC ratio increases in the zone of illuvial clay accumulation. Both clay films and relatively high FC/TC ratios are variously reported for soft weathered bedrocks in the database (Tables V and VI). Illuvial clay is often abundant and well preserved within bedrock fractures, where it is deposited by percolating water and protected from the disruptive forces of bioturbation (Graham *et al.*, 1994). The FC/TC ratio is higher in saprocks than in saprolite perhaps because the dominant clay in saprock is that which has been illuviated, whereas saprolite contains additional clay that has formed by *in situ* weathering of primary minerals, which generally has a larger particle size than clay that has been translocated. Similarly, much of the clay in soft weathered sandstone is illuvial, while shale contains abundant inherent clay that has not been sorted by within-profile translocation.

Fe- and Mn-oxides, noted in many soft weathered bedrocks (Table V), are redox-sensitive minerals that reflect water movement and redox status within soils (McDaniel and Buol, 1991; Turk *et al.*, 2012). In reduced form, both Fe and Mn are highly soluble and move with the water in the regolith. Upon reaching an oxidizing environment they precipitate as oxides. Mn-oxides are reduced and precipitate in higher Eh status environments than do Fe-oxides. Thus, Mn-oxides commonly occur in fractures and other macropores of saprolites (Schoeneberger *et al.*, 1992).

The implications of illuvial clay and Fe/Mn-oxide accumulations in soft weathered bedrock are (i) that the weathered bedrock is hydrologically connected to the overlying soil (Graham *et al.*, 1994), (ii) the illuvial clay increases the water-holding capacity of the soft weathered bedrock, (iii) the shrink–swell behavior of the clay promotes disruption of the bedrock fabric (Frazier and Graham, 2000), and (iv) abundant illuvial clay and Fe/Mn-oxides, particularly in saprolite (as opposed to less weathered saprock), may plug fractures and reduce their capacity to transmit water (Vepraskas *et al.*, 1991; Schoeneberger *et al.*, 1995; McKay *et al.*, 2005).

The relatively soluble minerals calcite and gypsum are described only for sedimentary bedrocks in the database (Table V). Data for sedimentary bedrocks in this study were predominantly from soils in the northern Great Plains region, where the rocks themselves contain calcite and gypsum and the arid or semi-arid climate inhibits dissolution and leaching of these minerals. However, pedogenic accumulations of calcite and opaline silica are commonly noted in saprocks in arid and semi-arid regions of the United States (e.g. Quade and Cerling, 1990; Boettinger and Southard, 1991; Graham *et al.*, 1994; Hirmas and Graham, 2011).

Root environment and water retention

When its upper boundary is within 1 m of the surface, soft weathered bedrock is well within the rooting depth of many plants. Root penetration is generally impeded in soils with a bulk density $\geq 1{\cdot}6\ \mathrm{Mg\,m^{-3}}$ (Grossman *et al.*, 1994; Brady and Weil, 1999) and the bulk density of all but two of the soft weathered bedrock types (the saprolites) exceed this value. Plant roots are commonly noted in all bedrock types (Table V), but they are often specifically described to occur within fractures, both by the NSSL database and the literature (Fisher and Stone, 1968; Schafer *et al.*, 1979; Daniels *et al.*, 1987; Stolt *et al.*, 1992; Zwieniecki and Newton, 1996; Graham *et al.*, 1997; Hubbert *et al.*, 2001b).

Fractures in soft weathered bedrock (Table V), inherited from the original rock and enhanced by weathering (Graham *et al.*, 1997), are channels through which water and roots move. Plant roots are found in weathered bedrock in a variety of climatic regimes. In California and other seasonally arid areas, roots are documented to penetrate weathered bedrock to depths of 9 m and more (Hellmers *et al.*, 1955; Saunier and Wagle, 1967; Jones and Graham, 1993; Hubbert *et al.*, 2001b) where they extract deeply stored water that ensures their survival during the dry season (Hubbert *et al.*, 2001a; Rose *et al.*, 2003).

The ability of regolith to store water is a function of thickness and the material's water-holding capacity. The maps in Figures 1, 2, 4, and 6 depict soft weathered bedrock occurrence within 1 m of the surface, but the databases provide no way to assess the thickness of the soft weathered bedrock zones. The pedon descriptions in the OSD and the NSSL characterization data rarely extend to even 2 m, so they typically describe only the upper part of the soft weathered bedrock. This is a major deficiency of the inventory, but we can make some general observations based on reports in the literature. Granitic saprock (Figure 3) in the western United States is typically on the order of several meters thick (Hellmers *et al.*, 1955; Isherwood and Street, 1976; Hubbert *et al.*, 2001a), although Wahrhaftig (1965) notes zones as thick as 30 m in the Sierra Nevada of California. Saprolites of gneiss and schist (Figure 7) on the Piedmont of the southeastern United States may be several meters thick (e.g. Calvert *et al.*, 1980; Pavich *et al.*, 1989; Oh and Richter, 2005) or tens of meters thick (Buol and Weed, 1991; Stolt *et al.*, 1992). Similar thicknesses are reported for soft weathered sedimentary bedrocks in the Ridge and Valley Province on the western flank of the Appalachian Mountains (Phillips *et al.*, 1998; McKay *et al.*, 2005). Soft sedimentary bedrock (Figure 5) can be > 2 m thick in eastern Montana (Schafer *et al.*, 1979).

The soft weathered bedrock of most lithologies has roughly the same capacity to retain plant-available water as the overlying soil horizons, with WHC ranging from 0·08 for granitic saprock to 0·22 for gneissic saprolite (Table VI). This WHC, combined with thicknesses typically several times greater than those of the overlying soils, makes the soft weathered bedrock zone an important reservoir of plant-available water. In eastern Montana, soft sandstone bedrock has a WHC identical to that of the overlying soil, and bedrock-stored water is accessed by rangeland grasses (Schafer *et al.*, 1979). The water held within soft weathered bedrock is so critical to tree and shrub survival in seasonally dry environments that without it the present vegetation communities would not exist (Arkley, 1981; Jones and Graham, 1993; Anderson *et al.*, 1995; Sternberg *et al.*, 1996; Zwieniecki and Newton, 1996; Hubbert *et al.*, 2001a, Graham *et al.*, 2010).

Water storage in soft weathered bedrock is not only critical for plants, it modulates throughflow to streams. When precipitation is sufficient, drainage from the soft weathered bedrock zone can support base flow in streams long after evapotranspiration has dried out the overlying soil (e.g. Bales *et al.*, 2011). Conversely, under drier climatic conditions, the soft weathered bedrock zone may impede deep percolation and movement of water to streams because there may be no excess water for drainage after the soft weathered bedrock has been fully recharged (Arkley, 1981).

Roots have been described in weathered bedrock in the central and eastern United States, but roots in more humid regions generally do not occur to the same depths as those in seasonally dry environments, such as in the western United States (Stone and Kalisz, 1991; Stone and Comerford, 1994; Schenk and Jackson, 2002). In humid regions, such as the southeastern United States, water is usually not limiting for plants. Nutrients, however, may be scarce in highly weathered and leached Ultisols formed on schists and gneisses (Buol *et al.*, 2011). Roots that penetrate deep into the weathered bedrock below these infertile soils may encounter higher levels of nutrient base cations (Ca, Mg, K) closer to the weathering front with fresh bedrock. The base saturation data for gneiss and schist weathered bedrocks (Table VII) do not demonstrate this, except for gneissic saprock, perhaps because only the upper part of the weathered bedrock zone was sampled.

The capacity to retain nutrient cations is indicated by the CEC. The CEC of weathered bedrock is relatively similar among the different lithologies, with the exception of shale. Clay minerals are a major source of CEC and shale has more clay than other soft weathered bedrock types (Table VII). Base saturation is highest in the soft, weathered sedimentary rocks. Where these rocks contain calcite or gypsum, the extracting solution dissolves some of those minerals resulting in high levels of extractable Ca and base saturation values $\geq$ 100%. The saprolites of gneiss and schist have the lowest base saturation values as a result of intense weathering and leaching.

Most plant roots and microbial activity are in the upper part of the soil, as indicated by the higher OC contents (Table VII), but roots in the weathered bedrock (Table V; Figures 3 and 5) produce high OC concentrations within the fractures where they occur (Frazier and Graham, 2000; Hubbert *et al.*, 2001b). Roots even several meters deep within the bedrock host mycorrhizal fungus whose hyphae penetrate throughout the mesofractures of the saprock (Egerton-Warburton *et al.*, 2003; Bornyasz *et al.*, 2005), adding small amounts of carbon to the soft weathered bedrock matrix. While the overall amount of carbon stored in weathered bedrock itself is low, soft weathered bedrock may indirectly contribute to increased carbon storage in overlying soils. The additional water supplied to vegetation by the soft weathered bedrock (Arkley, 1981; Anderson *et al.*, 1995; Sternberg *et al.*, 1996; Zwieniecki and Newton, 1996; Hubbert *et al.*, 2001a) increases total biomass and net primary production resulting in increased soil organic matter production at the site.

Advancing the inventory and understanding of soft weathered bedrock

This research has revealed several deficiencies in the inventory and understanding of soft weathered bedrock. First among these is the lack of systematic data on the thickness of soft weathered bedrock across landscapes. Without this information we cannot fully assess the function of the soft weathered bedrock zone. Extensive deep excavation is difficult, expensive, and disruptive, but remote sensing techniques such as ground-penetrating radar (e.g. Witty *et al.*, 2003; Breiner *et al.*, 2011) and shallow seismic refraction (e.g. Befus *et al.*, 2011) hold promise for gathering this crucial thickness data and incorporating it into soil surveys (Doolittle, 2012).

Improved information on soft weathered bedrock thickness needs to be complemented by a better understanding of its properties throughout the thickness. Some of these properties can be addressed with standard soil survey analyses as presented in this paper, but additional analyses are also needed. For example, systematically collected hydraulic conductivity data are lacking for both soils and soft weathered bedrock, but are critical for understanding water flow.

Perhaps equally important as the need for more data is the need for consistent use of standardized terminology so that those researching and inventorying soft weathered bedrock can clearly communicate their findings. We have noticed several inconsistencies or ambiguities in the use of terms. For example, 'saprolite' is often used to include 'saprock' which has quite different properties (Table I). Likewise 'grus', an accumulation of loose granitic granules, is sometimes used to refer to saprock, an intact, friable weathered bedrock condition - very different from grus. In soil surveys, saprock, and especially saprolite, are sometimes designated simply as 'C' horizons rather than 'Cr' horizons, which does not identify or highlight the bedrock fabric that is present. It may be that a new horizon designation of 'S', would be helpful for soft weathered bedrock, with suffix designations to make the important distinction between saprock and saprolite. Communication of scientific results is weakened when terms are not precisely applied, but there is also the danger that the important differences implied by the terms are not recognized at the outset, leading to poor sampling design.

Conclusions

Soft weathered bedrock within 1 m of the surface is widespread across the United States, and in some areas it is a common condition. The morphological properties compiled using the NSSL database show that soft weathered bedrock is pedogenically active. It is well documented that plants rely on soft weathered bedrock for a valuable source of stored water, but the supply of nutrients and potential for carbon storage by the weathered bedrock is unknown. Careful examination and characterization of soft weathered bedrock is necessary and relevant to pedological studies. Chemical and physical properties of soft weathered bedrock vary by lithology, but for many rock types, these properties are very similar to those of the overlying soil. In many respects soft weathered bedrock is soil — it has soil-like properties, performs soil-like functions, and is completely linked to the soil in a depth continuum. Because soft weathered bedrock zones are often thick relative to overlying soils, the impact on hydrologic processes and ecosystems can be significant, as in the case of water supply for plants and the regulation of throughflow runoff to streams. If we can accurately characterize the spatial distribution and physical, chemical, and morphological properties of soft weathered bedrock, we can begin to understand its full role in the environment. While the STATSGO database used in this research gives a broad overview of the extent and distribution of near-surface soft weathered bedrock, a much more accurate spatial evaluation will be possible when the SSURGO database is complete and available for use.

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