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Soil development on the WWI battlefield of Verdun, France

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Abstract

Much research has been done on how the physical environment can influence the outcome of battle, but few have studied the inverse: the effects of warfare upon the environment. The goal of this research is to characterize and help understand soil development within areas disturbed by explosive munitions on the WWI battlefield of Verdun, France (1916). Encompassing an area of 29,000 km^2, the battlefield remains one of the most heavily shelled of all time. Twenty-seven pedons were sampled and described, at three sites on the battlefield; some pedons were within artillery craters while others were on adjacent "undisturbed" soils. Site selection reflected the diversity of bedrock and drainage characteristics across the study area. Soil development was characterized within the crater bottoms and sides. Many craters penetrated the shallow limestone bedrock, and blasted out fragments of limestone on nearby undisturbed pedons had already been incorporated into the profile. Despite the short period of time since the battle (88 years), measurable amounts of weathering and pedogenesis has occurred in the soils within the craters. A major pedogenic process operative here is the accumulation and decomposition of organic matter, which is intimately associated with (and aided by) earthworm bioturbation. Based on elemental analysis of the fine earth fraction, measurable amounts of leaching and weathering have occurred in the 88 years since the battle. This study provides insight into the ability of a landscape to recover following a catastrophic anthropogenic disturbance.

Keywords: Pedoturbation; Pedogenesis; Bombturbation; WWI; War and environment; Leaching

1. Introduction

Warfare can be a horribly violent activity. It is also a powerful geomorphic agent (Bazzaz, 1983; Hupy and Schaetzl, 2006). As an agent of landscape disturbance, warfare is often larger in magnitude than many "natural" forms of disturbance, e.g., hurricanes, wind storms and earthquakes. Warfare is also distinctive because it is an *anthropogenic* agent of change, capable of causing destruction over short periods of time (Westing, 1980), especially warfare of the 20th century (Hupy and Schaetzl, 2006). Despite the magnitude of disturbance associated with modern warfare, however, it continues to be overlooked as a significant form of anthropogenic disturbance (King, 2001).

The ecological ability of a landscape to recover from various forms of disturbance is defined as *resilience* (Miles et al., 2001), and is commonly measured using bio-ecologic indicators (Wali, 1999; Miles et al., 2001; Usher, 2001). The drawback to relying solely on these types of measures to assess landscape resilience is that the entirety of the landscape is not taken into account; most of these parameters ignore surface instability and degradation, as well as soils. Geomorphologists have, therefore, expanded upon the concept of landscape resilience by including geomorphic factors into what is now called *sensitivity*, i.e., the stability vs. instability of a landscape (Brunsden and Thornes, 1979; Phillips, 1997). Under stable landscape conditions, soils can develop progressively and relatively uninterruptedly (Johnson and Watson-Stegner, 1987). Thus, we suggest that soils of stable surface or slope conditions.

Most soil-related applications in this regard have revolved around long-term landscape studies (Dan and Yaalon, 1968;

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Parsons et al., 1970; Gile et al., 1981; Balek, 2002). For similar reasons, soils have largely been ignored in *short-term* landscape recovery studies (Thomas, 2001). Indeed, of the research that has examined soil properties as an indicator of short-term recovery under both natural and human forms of disturbance (Paton et al., 1976; Roberts et al., 1988; Schleuss et al., 1998; Grieve, 2000, 2001; Beyer et al., 2001; Mueser and Blume, 2001), most have focused on disturbance by activities such as mining or logging (Vimmerstedt and Finney, 1973; Roberts et al., 1988; Lebedeva and Tonkonogov, 1995; Wali, 1999; McPherson and Timmer, 2002).

Our focus is on soil disturbance and recovery resulting directly from the actions of warfare. The literature on this topic is limited, although some studies have examined the ability of a soil/surface to recover after being subjected to tank traffic (Prose and Metzger, 1985; El-Baz, 1992; El-Baz et al., 1993; El and Al, 1996; Nichols and Bierman, 2001). Research on soils as indicators of landscape recovery following anthropogenic disturbance, especially the direct impacts of war, has been minimal.

Recently, we introduced the term "bombturbation" for the cratering of the soil surface and the concomitant pedoturbation imposed by explosive munitions (Hupy and Schaetzl, 2006), in an attempt to draw attention to the impact of warfare on soils. For example, the WWI western front in Europe extended 725 km from the North Sea to the border of neutral Switzerland (Keegan, 1998). With an average depth of 20 km on either side, the amount of land cratered by artillery is a staggering 29,000 km^2. In our current paper, we expand on our bombturbation research by providing more information on the effects of warfare as applied to soil morphology and development, in effect addressing the long-term, pedogenic and geomorphic *ramifications* of warfare, or the pathways of soil development on those particular landscapes following such a disturbance. To state that the Verdun landscape has recovered is a misnomer; landscape recovery would imply the landscape has reverted back to its original state. While the forests have returned to a given extent, the landscape, when viewed from a soils perspective (the soilscape), is highly heterogeneous. Therefore, the objectives of this paper are to characterize and explain soil development in areas previously (88 years ago) disturbed by explosive munitions. Our data can be used to better understand the role of bombturbation in increasing the long-term heterogeneity of soil landscapes by modifying the direction of post-disturbance pedogenesis at isolated sites.

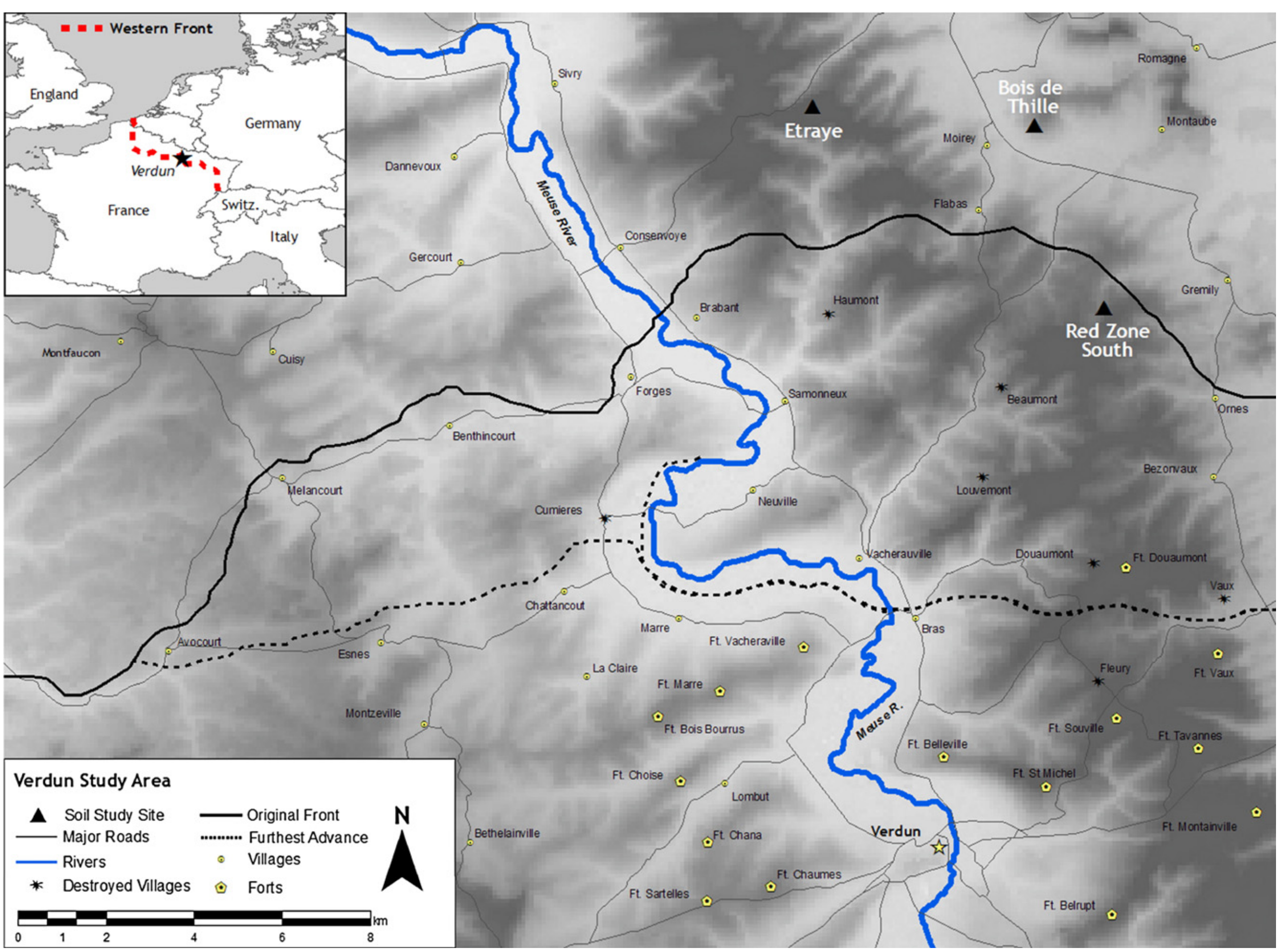

Fig. 1. Locations of study sites in relation to key elements of the Verdun, France battlefield. Study sites are located in fringe areas where the most landscape disturbance took place, between the two battlefield "fronts" indicated on the map.

2. Study area

2.1. Historical background

The WWI battle of Verdun, France, in 1916, remains one of the most intense battles fought between two nations (Germany and France) in all of human history (Fig. 1). It is considered a textbook example of a battle of attrition. Both nations expended millions of rounds of ammunition and sent hundreds of thousands of men to their death in less than eight months of fighting. Historical accounts and contemporary descriptions have documented the intense and widespread landscape disturbance associated with this battle, not to mention the great loss of life (Clermont-Ferrard, 1919; Horne, 1993; Brown, 1999; Martin, 2001; Hupy, 2006). Nonetheless, beyond descriptions of the post-battle landscape appearance and brief mentions of the contemporary landscape (Webster, 1996; Westing and Pfeiffer, 1972), post-disturbance landscape development at Verdun has never been studied.

Historically, the Verdun battlefield is one of the best documented and, in the decades since the war, unaltered battlefields in the world. That is, in the post-WWI period, large parts of the battlefield have been cordoned off by the French government and left to recover with minimal human intervention, facilitating this research. Although several notable areas are maintained as park-like memorial settings, the majority of the battlefield is treated as a mass grave for the hundreds of thousands of uncounted dead. For these reasons, the battlefield retains millions of artillery craters and remnants of war (Fig. 2).

2.2. Physical setting

The Verdun area receives some of the highest amounts of precipitation (700–800 mm annual mean) in Europe. Precipitation events occur 150–200 days/year (Montagne, 2003). Mean January temperatures range from 0–2 °C in the Meuse River Valley and 0–5 °C on the surrounding uplands. Average July temperatures range from 15–18 °C.

Pre-war deciduous forests in the Verdun area were dominated by European beech (*Fagus sylvatica*), European hornbeam (*Carpinus betulus*), European oak (*Quercus sessiflora*) and English oak (*Q. pedunculata*). Today the most common species is European beech, with large expanses of Austrian pine (*Pinus nigra*). Austrian pines have been planted primarily in areas that are heavily visited, since it is believed the trees cast a memorial like, soft lighting. Some attempts have been made to diversify the forests, but the magnitude of disturbance in some areas and the sheer size of the battlefield have hindered efforts to restore the forest into its original state.

Bedrock at Verdun consists of gently dipping limestones and shales that comprise the eastern portion of the Paris structural basin (Johnson, 1921). The dominant geologic/geomorphic feature of the region is a series of northeast–southwest trending cuestas, thereby providing the region with ≈200 m of local relief. The French Fort Douaumont, at 396 m elevation, is situated atop a cuesta ridge, at the highest point of the battlefield while the eastern portions of the battlefield, on the fringes of the Woevre River valley, are roughly 200 m above sea level. Erosion-resistant, almost pure, limestone of the late to mid Jurassic Oxfordien (154–146 Ma) Formation makes up the ridges while a weaker, marly limestone, incorporated with thin sequences of shale, occupies the valleys.

The Woevre Valley, east and below the limestone escarpments, is underlain by soft, erodable shales and poorly-drained, clay-rich soils (Johnson, 1921). In upland areas where a marl-rich limestone forms the bedrock, perched water tables are common from fall until late spring when snowmelt and spring rains impact frozen soil (Ollivier Marcet *pers. comm.* 2003).

Fig. 2. A typical example of heavy disturbance on the Verdun cratered landscape near Fluery, France. Source: Joseph P Hupy, 2003.

Table 1
Characteristic soils on the battlefield of Verdun, France

French soil classification	Landscape position	USDA-NRCS equivalent	Parent material
Rendzina	Ridge shoulders crests	Rendolls	"Pure" limestone
Brunified Rendzina	Ridge crests	Rendolls	"Pure" limestone
Calcareous Brown Soil	Ridge back and foot slopes	Hapludalfs	Limestone
Calcic Brown Soil	Ridge Crests	Hapludalfs	Limestone and colluvium
Gley	Valley bottoms	Hydraquents	Shale and colluvium
Pseudogleys	Valley bottoms	Aquepts	Shale and colluvium

Sources: United States. Soil Conservation Service, (1975); Montagne (2003).

Most soils at Verdun have formed in residuum or colluvium, and thus, soil formation in the region is influenced by the generally shallow bedrock, landscape position, and the shallow-to-deep water tables (Table 1). Most of the soils in the valleys are in the poorly-drained class (Soil Survey Division Staff, 1993). Upland soils are generally shallow to the "pure" limestone bedrock, which produces little residuum (Duchaufour, 1982). Soils on ridge tops are typically Calcic Browns. Steeper slopes that experience more runoff and soil erosion contain Rendzina soils. When Rendzina-type soils occur on ridge crests they are often slightly thicker and show more development than when on slopes. Therefore, the ridgecrests often contain Brunified Rendzinas while the ridge shoulder slopes contain especially thin Rendzina-type soils (Table 1).

3. Methods

3.1. Field methods

In order to assess the effects of explosive munitions on soil development, we excavated and sampled undisturbed soils adjacent to artillery craters, as well as disturbed soils within craters (Fig. 3). We chose sample sites where artillery shell disturbances were widely scattered, i.e., where large areas of undisturbed soils, adjacent to craters, were also available for sampling (Fig. 1). Site selection criteria were stratified to include all three of the main types of soils in the battlefield (1) soils at the Etraye site are Brunified Rendzinas over nearly 'pure' limestone bedrock, (2) Red Zone soils are Calcareous Browns developed on a more weathered but less 'pure' limestone, and (3) at the Bois de Thill study site, Pseudogleys are mapped on the nearly pure clay colluvial deposits in the Woevre River valley (Table 2; Fig. 1).

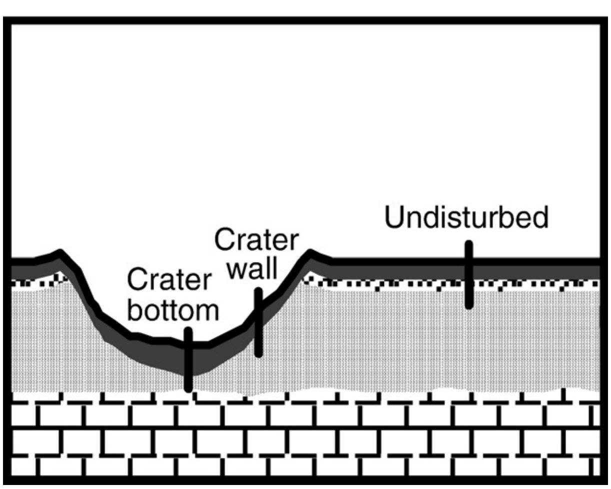

Fig. 3. Schematic diagram of a typical artillery crater and its rim of blown-out debris on the Verdun Battlefield. Although crater size varies, a typical crater is ~50 cm deep and ~3 m in diameter. The locations of the three sampled pedons for each of these craters is shown. Pedons were sampled at depths of 10, 20, 30, and 50 cm below soil surface.

We used a backhoe to dig a trench 1 m long across three representative artillery craters at each of the three study sites (nine trenches in all; Fig. 3). Prior to excavation, crater depth and diameter along the long and short axis were recorded. The trenches extended across the crater and onto the undisturbed soils adjacent to it. In some instances, excavation encountered shallow bedrock or the water table. Data from undisturbed soils adjacent to the craters were compared to data from the disturbed sites to assess the impact of disturbance.

Table 2
Typical "undisturbed" pedon descriptions [a] from the Etraye, Red Zone, and Bois de Thill study sites

Horizon	Depth (cm)	Color [b] (moist)	Structure [c]	Consistence [d] (moist)	Bdy [e]	Coarse frags [f] (est. by vol.)
Etraye						
A1	0–19	10 YR 3/1	3 m/c gr	VFI	CI	25% CG
A2	19–36	10 YR 4/3	2 m gr	VFI	GI	60% CG
Cr1	36–53	10 YR 6/6	2 m sbk	FI	GW	60% CG
Cr2	53–64	10 YR 6/6	2 m sbk	FI	GW	80% CG
R	64+	10 YR 7/8	–	–	–	Limestone bedrock
Red Zone						
Oi	0–4	10 YR 3/2	–		AS	None
A	4–17	10 YR 3/2	3 m gr	VFI	CS	10 MG
Bw	17–29	7.5 YR 3/4	3 f gr/sbk	FR	CW	20 CB 10 CG
Cr1	29–55	5 YR 3/4 10 YR 8/2	1 vf abk	VFR	GW	50 CB 25 CG
Cr2	55+	10 YR 6/4	1 vf abk	L	–	70 CB 20 CG
Bois de Thill						
A	0–22	10 YR 3/2	2 f/m gr	FI	CS	None
Bg	22–59	5 YR 5/4	3 m/c sbk	VFI	CS	None
Cg1	59–91	5 YR 4/6 5 YR 5/2	2 m/c sbk	VFI	GW	None
Cg2	91+	5 YR 4/6 5 YR 4/6	2 m/c sbk	VFI	–	10 MG

[a] Descriptions based upon Soil Survey Division Staff, 1993. Horizons <3 cm thick were not described.
[b] Hue, Value, and Chroma according to Munsell Soil Color chart.
[c] Abbreviations: vf: very fine, f: fine, m: medium, c: coarse, gr: granular, sbk: subangular blocky, abk: angular blocky.
[d] Abbreviations: VFI: very firm, FI: firm, FR: friable, VFR: very friable, L: loose.
[e] Abbreviations: AS: abrupt smooth, CS: clear smooth, CW: clear wavy, CI: clear irregular, GW: gradual wavy GI: gradual irregular, GW: gradual wavy.
[f] Abbreviations: CB: cobbles (76–250 mm), CG: coarse gravel (20–76 mm), MG: medium gravel (5–20 mm).

Soil profiles were described and sampled at three locations along the face of each of the nine backhoe trenches (27 profiles in all), according to NRCS guidelines (Soil Survey Division Staff, 1993). Representative samples of approximately 500 g were removed from the profile face at depths of 10, 20, 30, and 50 cm, air-dried in France, and transported back to the USA for further analysis.

3.2. Laboratory methods

Incipient soil development is often quantified by determining the amount of translocation of soluble vs. insoluble constituents, which may be reflective of the amounts of weatherable and translocatable minerals vs. those that are more stable (Singh et al., 1988; Howard et al., 1993). Minerals such as tourmaline and zircon are highly resistant to weathering and may remain in the soil profile while other, less resistant minerals like olivine, plagioclase feldspars, and biotite will be preferentially weathered and their byproducts removed. Elemental data are often used as surrogates for mineralogical data (Murad, 1978; Santos et al., 1986; Busacca and Singer, 1989) because some elements can be linked to one or only a few minerals, e.g., zirconium mainly derives from the resistant mineral zircon, and titanium resides mainly in the resistant minerals rutile, tourmaline, and anatase. Thus, by comparing elements from minerals that are resistant to elements that derive largely from weaker, weatherable minerals, it is possible to use elemental data as surrogates for weathering and translocation in soils (Murad, 1978; Schaetzl and Anderson, 2006). Inherent in any of these types of analysis is the assumption of initially uniform parent materials, as well as comparable bulk densities among the horizons being examined. Whereas we could not hold each of these precursors constant, their variability is minimal in the soils under study here.

We estimated the degree of weathering and translocation in these soils by comparing the ratios of elements from easily weathered minerals, e.g., Ca, Mg, Na, K, and Na, to elements from minerals that are more resistant to weathering and translocation (Zr, Ti) (Beavers et al., 1963; Evans and Adams, 1975; Howard et al., 1993; Lichter, 1998). When examined by depth, such data can be used not only to evaluate the uniformity of the "control" soils, e.g., the undisturbed soils adjacent to the craters, but also to assess pedogenic development. To generate these data, elemental analyses were performed by X-ray fluorescence (XRF). XRF major element (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, Rb, Sr, and Zr) analyses were reduced by a fundamental parameter data reduction method, while XRF trace element data were calculated using standard linear regression techniques. From these data, we chose the ratio (Zr+Ti)/(Ca+Mg+K+Na) to illustrate the degree of translocation of relatively mobile vs. immobile elements, and hence weathering and soil development.

Soil pH, particle size data, and organic matter (OM) contents were also determined for each sampled horizon. Prior to analysis, each sample was oven dried at 100 °C. Coarse fragments were removed from the dried samples by gently crushing and passing the soil through a 2-mm sieve. Soil pH values were determined in a 2:1 water:dry soil suspension using a handheld electronic pH meter (Model IQ150, Scientific Instruments Inc.). Particle size analyses were conducted by pipette (Day, 1965) on all but O horizon samples. Loss on ignition (LOI) was used to estimate the organic matter contents of all samples (Davies, 1974).

4. Results and discussion

At each study site, three typical artillery craters – small, medium and large – were selected for study (Table 3). Three pedons were then described and sampled from a trench that began in the center of each crater. Because of the large amount of data we amassed (27 pedons), this paper provides only a general discussion of the crater soils, with comparisons to their representative undisturbed pedons (Tables 2 and 3). Our goals in this discussion are two-fold: (1) how the soils and landscape have been disturbed by the artillery explosions of the 1916 Verdun battle, and (2) to what degree they have (pedogenically) recovered from this disturbance.

4.1. Morphologic characteristics

4.1.1. Red Zone soils and craters

The well drained, Calcic Brown soils at this study site support mainly European Beech forest. Like many sites at Verdun, the crater bottoms here have accumulated roughly 10 cm of leaf litter, branches, and other forms of forest debris, as is typical in depressional sites in forests (Schaetzl, 1990; Schaetzl et al., 1990; Meyers and McSweeney, 1995). The combined thicknesses of the O and A horizons in the craters (≈20 cm) are substantially greater on the crater bottoms than on undisturbed sites (≈4 cm) nearby, after only 88 years. O horizon thicknesses on the steep crater sides are usually about half (≈6 cm) of those in the crater bottoms. Because the crater bottom soils have only been developing several decades, the boundary between the O and A horizons and weathered bedrock in the crater bottoms is typically abrupt or clear, due to lack of bioturbative activity below the point of contact with the bedrock. Many craters here penetrate into the limestone bedrock, and fragments of bedrock have been ejected from the crater area, onto adjacent soils. Thus, A horizons in the nearby soils contain numerous fragments and lenses of limestone gravel channers, usually several cm below the soil surface because of 88 years of bioturbation which has

Table 3
Dimensions of, and soil type within, excavated craters on the Verdun battlefield

Study site (crater #)	Diameter 1 (cm)	Diameter 2 (cm)	Depth (cm)	Soil type
Red Zone (1)	620	640	106	Calcic Brown
Red Zone (2)[a]	232	256	38	Calcic Brown
Red Zone (3)	396	402	59	Calcic Brown
Bois de Thill (1)[a]	430	352	52	Pseudogley
Bois de Thill (2)	396	362	44	Pseudogley
Bois de Thill (3)	276	282	36	Pseudogley
Etraye (1)[a]	356	320	57	Rendzina
Etraye (2)	470	474	103	Rendzina
Etraye (3)	472	476	104	Rendzina

[a] Pedon adjacent to crater used as representative undisturbed pedon for this site.

acted to lower the coarse fragments by emplacing finer materials above them (Johnson et al., 2005, 1987; Whitford and Kay, 1999; Balek, 2002). Evidence of ongoing bioturbation stems from the numerous earthworm castings and filled in krotovinas within the soil column.

As expected, gravel and broken fragments of bedrock are abundant in crater bottoms, generally increasing in abundance and size with depth. For example, in most crater bottoms, which have O–A–C profiles, the O horizons contain no gravel, the A horizons 5–25% coarse fragments, and the C horizons 80–90% coarse fragments. Some crater soils show evidence of a yellowish brown (10 YR 5/4) Bw horizon. The weak B horizon may be forming in residual, fine-textured, previously weathered material within the crater, left behind by the blast. Craters that lack this type of B horizon usually were excavated entirely to fresh bedrock. In some craters, fine-textured, pinkish grey (7.5 YR 7/2), parent material exists and is described as a C horizon.

Since the battle of Verdun, shattered bedrock within the craters has taken on a weathered appearance. Unweathered, hard limestone bedrock had to be chipped out with a geologic hammer for examination. In contrast, the weathered Cr horizon rock nearest to the crater bottom is visibly weathered and can be broken into smaller pieces without tools. Cr fragments (saprolite) have developed weathering rinds and clay minerals have neoformed along fracture lines. Weathered material in crater bottoms follows fracture lines into the limestone bedrock, probably generated from, or at least exacerbated by, the artillery blast. Eventually, this saprolitic material grades with depth into unweathered bedrock. Bedrock at the same depth below adjacent undisturbed pedons appears completely unweathered.

4.1.2. Bois de Thill soils and craters

The Pseudogley soils here are poorly drained, with redoximorphic features present throughout the profile — a result of a seasonally high, unconfined water table and fine parent material textures with low permeabilities.

O horizons are thin within the crater bottoms, due not only to the labile nature of forest liter, but mainly because of the high rates of earthworm bioturbation which act to incorporate the raw organic material into the mineral soil and facilitate humification. Earthworm casts dominate the strong granular structure within A (and even O) horizons in the crater bottoms. A horizon thickness in crater bottoms is similar (~20 cm) when compared to horizons on the crater side and adjacent undisturbed pedons. However, crater bottom A horizons were noticeably darker (black; 10 YR 2/1) and exhibited an abrupt horizon boundary to the underlying Cg horizon. Soils adjacent to the crater had very dark brown (10 YR 3/2) A horizons and boundaries that were more gradual in their contact to the B horizon below. The gradual contact was due to earthworm bioturbation that blended the A and B horizon materials. In the crater bottom, the high water table inhibited this type of bioturbation.

Soils in the crater bottoms here typically had A–Cg profiles. The upper Cg horizons contained many Fe-concentrations, and Fe-depletions were common in the lower Cg horizon. The undisturbed soils contained weak Bg horizons above Cg horizons, again pointing to persistent high water tables. For this reason, the soils at Bois de Thill are not as developed as at Red Zone. The main pedogenic processes here are melanization, gleyzation and bioturbation, none of which promote strongly horizonated profiles. Horizonization boundaries are primarily discernable by color contrast — the black A (10 YR 2/1) horizons vs. the yellowish red (5 YR 4/6), gleyed Bg horizons below. The main expression of profile development here is the strongly developed A horizons, the formation of which has been promoted by earthworm bioturbation and melanization. The Ca-dominated soil system here not only favors earthworms ecologically, but also slows humification processes, thereby facilitating the accumulation of humified organic matter, and hence, dark A horizons (Schaetzl, 1991a,b). Although a few earthworm krotovina penetrate into the upper Cg horizon, the poorly-drained conditions at this site largely confine earthworm activity to the upper profile. The constrained earthworm activity is apparent not only in the color contrast between the horizons, but also in soil structure, which changes from a moderate granular in horizon A to moderate subangular blocky below.

4.2. Etraye soils and craters

The shallow Rendzina soils here have developed in residuum from nearly pure limestone bedrock. Despite the upland location, standing water is present throughout most of the year in some of the deeper craters, due to a seasonally perched water table (French Forest Service, unpublished data). Because the craters were excavated and sampled during the late summer, when water tables were low, the soils within contained few redoxymorphic features. Bedrock is not deep at this site; the only deep craters were those stemming from (presumably) large caliber artillery rounds. Worm casts, middens and activity are so common here that an O horizon was observed within only two of the three crater bottoms. Even where present, O horizons in crater bottoms (in late summer) are thin (4–5 cm).

Here, A horizons overlie highly weathered C horizons comprised of fragments of limestone bedrock set amidst clay-rich peds, with tongues of organic-rich material extending down into bedrock fractures. The A horizon on the bottom of crater 2 was 28 cm thick, whereas the Cr horizon below extends to 43 cm, below which lies mostly unweathered limestone bedrock.

4.2.1. Summary: pedon morphology

Artillery craters are sites of preferential organic matter accumulation; pedons within craters at each site exhibited thicker and darker A horizons, indicative of increased melanization, when compared to undisturbed pedons. A horizons, thick within the crater bottoms, thinned when progressing towards the crater rim. O horizons followed the same pattern as A horizons at the Red Zone site, but were largely absent within craters at the Bois de Thill site and thin within craters at Etraye. The relative lack of O horizons, coupled with the thicker, more organic-rich A horizons, at the latter sites, was probably due to abundant earthworm bioturbation near the surface of crater bottoms. Soils at both sites were suggestive of seasonally high water tables and poor drainage. The Etraye site was similar to the Red Zone site in that both soils were over limestone bedrock, but bedrock at

Red Zone was not nearly as "pure," providing better drainage and a deeper weathering profile. Soils at Bois de Thill formed in poorly-drained colluvial deposits with a water table close to the surface most of the year. Weathering of previously exposed bedrock was easily observed at the Etraye and Red Zone sites. Post-war soil development within craters at the Etraye and Red Zone sites was, therefore, readily apparent, as exemplified by the development of A horizons, weak B horizons in some of the crater bottoms, and by the presence of Cr horizons that were, prior to disturbance, unweathered limestone bedrock.

4.3. Physical and chemical characteristics of the soils

Undisturbed soils at the three study sites generally had USDA textures that ranged from loam to clay loam to clay. Textures were fairly uniform throughout each of the soil profiles within the craters and undisturbed soils, with clay contents showing little to no systematic increase with depth (Fig. 4). Some of the undisturbed soils show evidence of a slight increase in clay in the B horizon. We did not expect, nor did we discover, evidence of lessivage in the young, Ca- and base cation-dominated crater soils (Duchaufour, 1982; Schaetzl and Anderson, 2006).

Soil pH values generally increased slightly with depth in each crater pedon at the three study sites (Fig. 5), suggesting that a small but measurable amount of leaching and acidification has occurred in the 88 years since disturbance. Undisturbed soils were generally more acidic (≈0.5 pH) and leached than those within the craters, largely owing to their greater age. The change in pH with depth on both undisturbed soils and within craters is less at Etraye and Red Zone than at Bois de Thill, because of the shallow limestone bedrock which acts as a strong buffer. Nonetheless, the fact that pH changes this noticeably with depth in these highly buffered limestone soils is an indication that base cations weathered from the limestone are being leached. The high concentrations of acidic (beech) organic matter within the crater bottoms likely contributed to the rapid acidification in the upper crater profiles.

Organic matter (OM) contents are significantly greater within crater profiles, especially in the upper profile, when compared to undisturbed adjacent soils at each of the three study sites (Fig. 6). In all but one of the nine craters, the organic matter contents are higher in the crater bottom pedons than in those on the crater sides. OM data show that significant amounts of organic matter have accumulated within the crater bottoms at

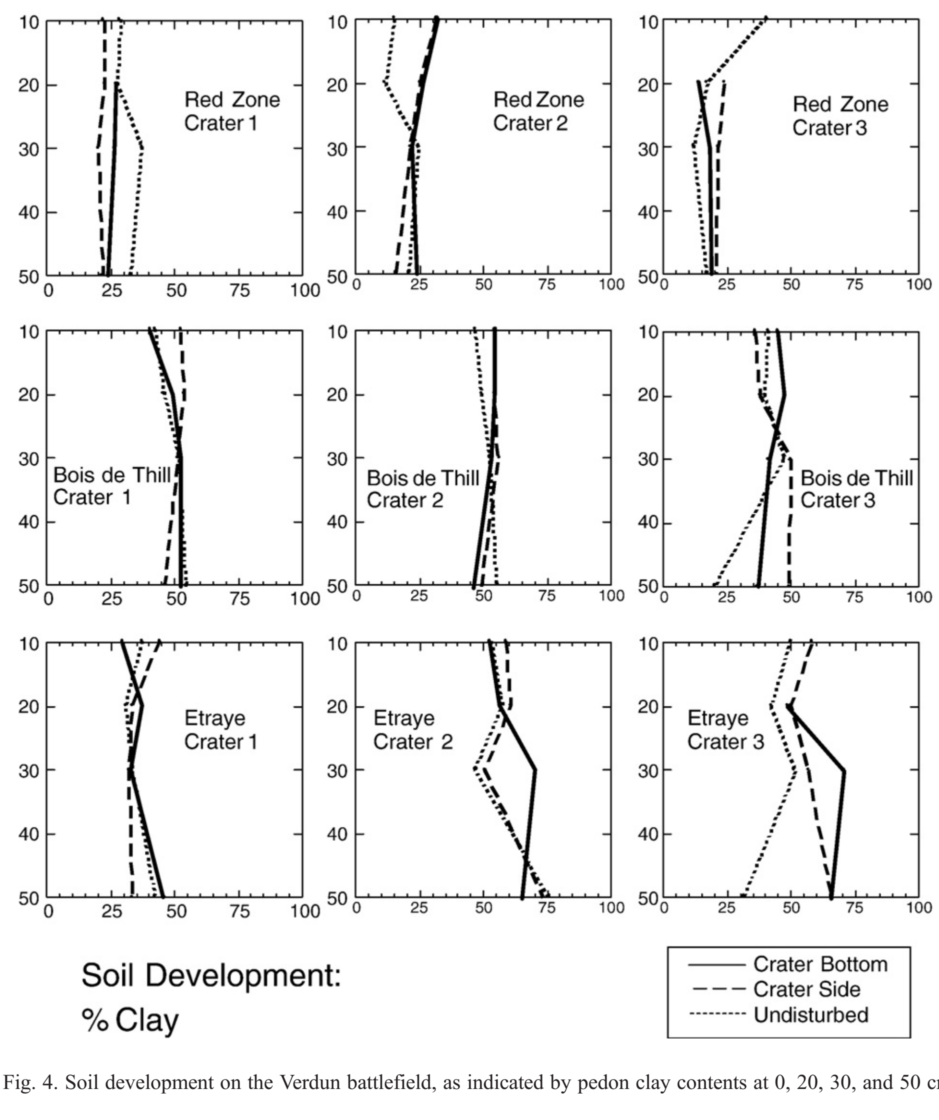

Fig. 4. Soil development on the Verdun battlefield, as indicated by pedon clay contents at 0, 20, 30, and 50 cm.

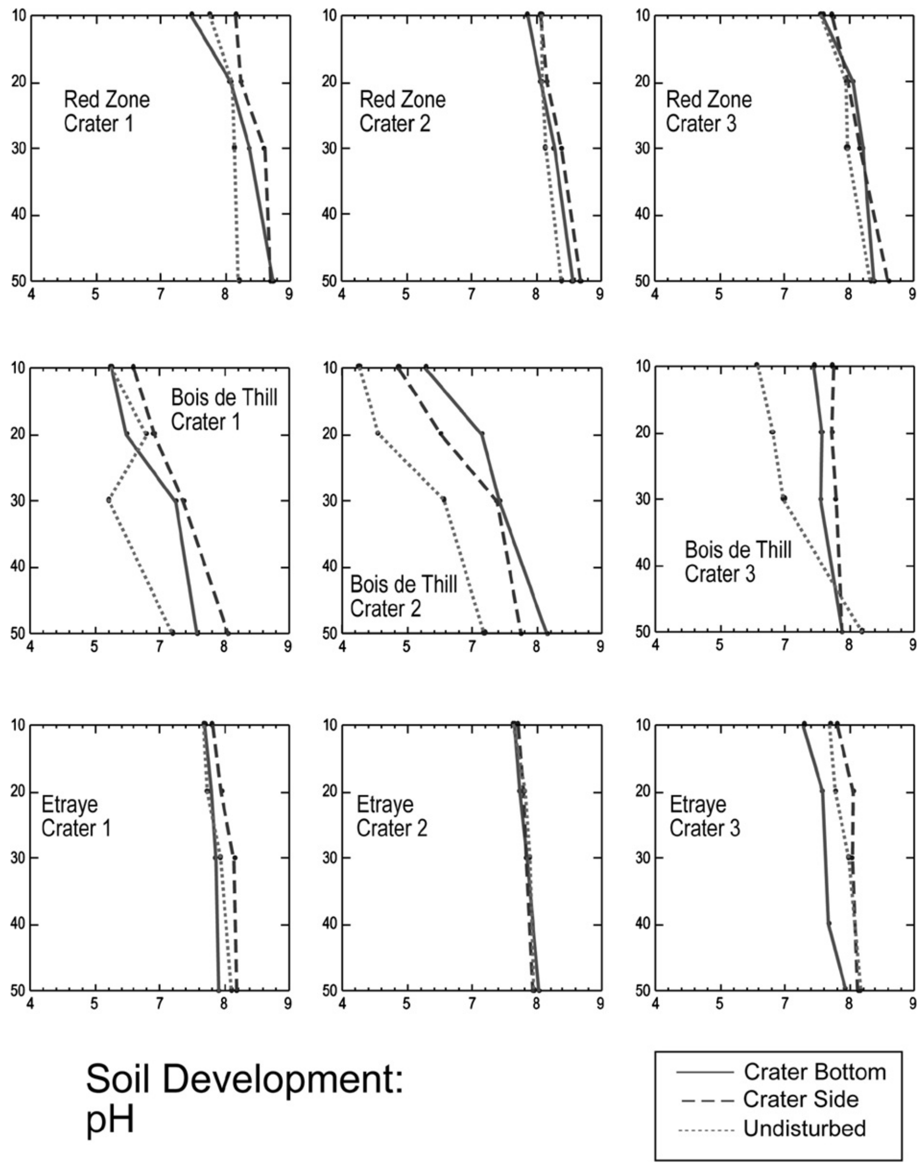

Fig. 5. Soil development on the Verdun battlefield, as indicated by pedon pH levels at 0, 20, 30, and 50 cm.

each of the study sites. Not only does the development of O and A horizons illustrate the vestiges of soil formation in formally exposed unaltered bedrock, but also that a slightly different suite of pedogenic processes are occurring in the crater bottoms in the adjacent, undisturbed soils (Liechty et al., 1997).

Selected XRF data were ratioed, so as to reflect primary mineral weathering (Fig. 7). As mentioned previously, we chose the [(Zr+Ti)/(Ca+Mg+K+Na)] to compare data for soil minerals that are resistant to weathering to those that are more easily weathered and translocated from the profile. Higher ratios indicate more weathering and translocation. Results from the XRF ratios reveal that, as expected, a general decrease in weathering can be observed, with depth, in the undisturbed pedons (Fig. 6). Many of the undisturbed pedons appear to show a decrease in "weathering" in the uppermost horizon. This is likely an artifact of the battlefield disturbance, especially because of additions of base-rich limestone parent material blasted onto the soil surface, only to be later weathered and incorporated into the upper profile by bioturbation. In all cases, the low XRF ratios in the deepest horizons of the undisturbed soils attest to the utility of the ratio as a weathering proxy in young soils.

Depth plots of the XRF ratios illustrate that the undisturbed soils are more leached and weathered, especially in their upper profiles, than are the disturbed soils within the craters (Fig. 6). With only one or two exceptions, the undisturbed soils generally have higher XRF ratios than the soils within the craters. Exceptions occur in craters at the Bois de Thill site; ratio values there may have erratic patterns because the parent material is colluvium brought in from higher elevations of the Meuse escarpment to the west, and not material weathered in situ from bedrock, as is occurring at the Etraye and Red Zone sites.

The convergence of the XRF ratios with depth, for both the undisturbed and disturbed soils within the craters, points to the shallowness of the profiles of the former, such that at ≈50 cm the undisturbed pedons are usually almost as "unweathered" as

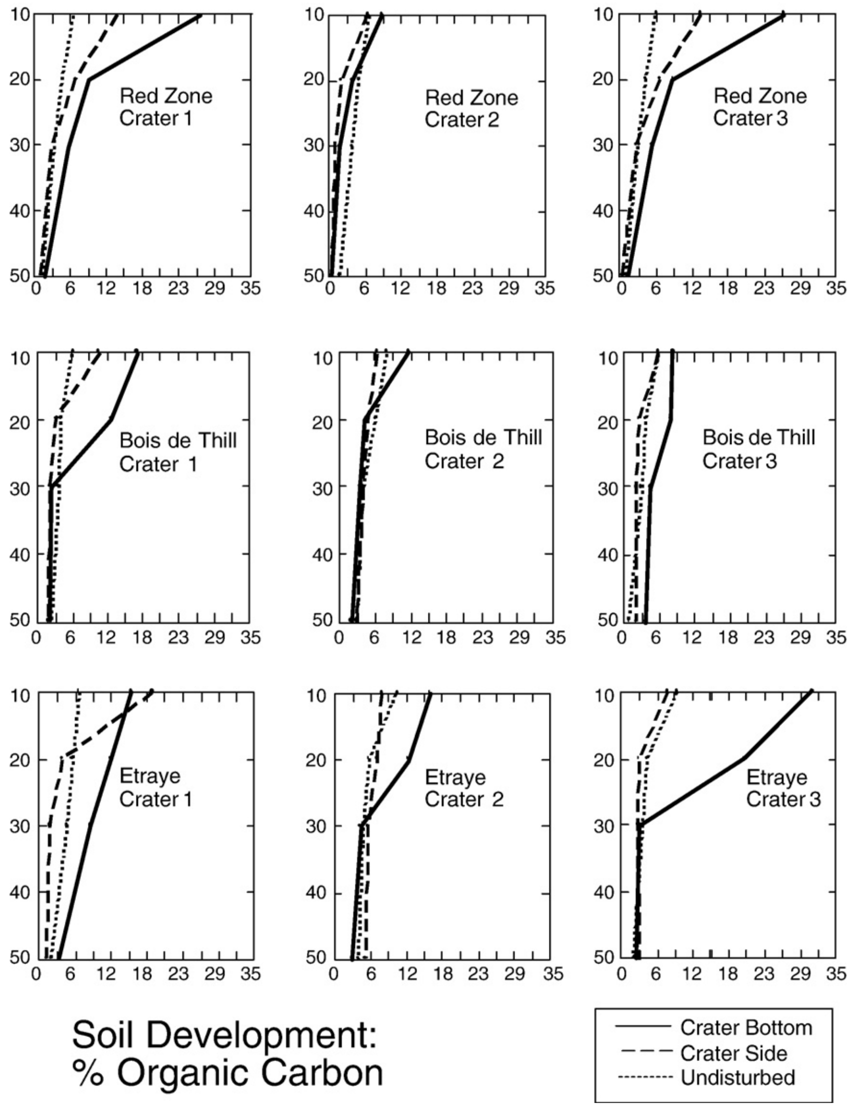

Fig. 6. Soil development on the Verdun battlefield, as indicated by pedon % organic carbon levels at 0, 20, 30, and 50 cm.

the newly exposed material in the crater bottoms (Fig. 7). This "equifinality" suggests that the ratios at depth are indicative of slightly weathered bedrock and residuum, which is also currently exposed in the crater bottoms. Bedrock and rubble in the craters has only recently been exposed for 88 years. Nonetheless, measurable amounts of weathering, leaching and acidification have occurred in the crater soils.

4.4. Soil development at Verdun

Our data (Figs. 3–6) suggest that measurable amounts of soil development have occurred within the craters since the 1916 battle of Verdun. After the initial disturbance 88 years prior to the study, no pedogenic horizons or recognizable "soil" likely existed in the crater sides or bottoms — only fractured limestone bedrock and associated rubble. Since that time, most of the newly exposed surfaces within the craters have developed thick accumulations of organic matter, the then-fresh bedrock has been weathered and some of its byproducts leached. Incipient soil development in the craters is indicated by acidification of the near-surface horizons, as well as measurable soil development in the weathering and translocation of minerals in the upper profile (Fig. 7).

Craters have acted as focal points for runoff, litter, and sediments washed from the adjoining soil surface. The concentrated movement of water tends to (1) attract micro and macrofauna, which (2) accelerate the humification of the organic matter within (Runge, 1973; Schaetzl and Schwenner, 2006). The faster than expected weathering of the bedrock fragments in the crater bottoms (Fig. 6) is likely due to the increased amounts of water moving through the craters. In this regard, the gravitational energy associated with water is driving soil development, and this type of development is preferentially stronger within the craters, which are foci for water movement (Runge, 1973).

Bioturbation has also dramatically affected pedogenesis and soil "recovery" on the Verdun battlefield (*cf* Schaetzl and Schwenner, 2006). The type and degrees of horizonation, and the rapidity by which incipient soil horizons have formed within craters, would not have occurred in the absence of key bioturbation processes. Worm activity is notable, even deep into the

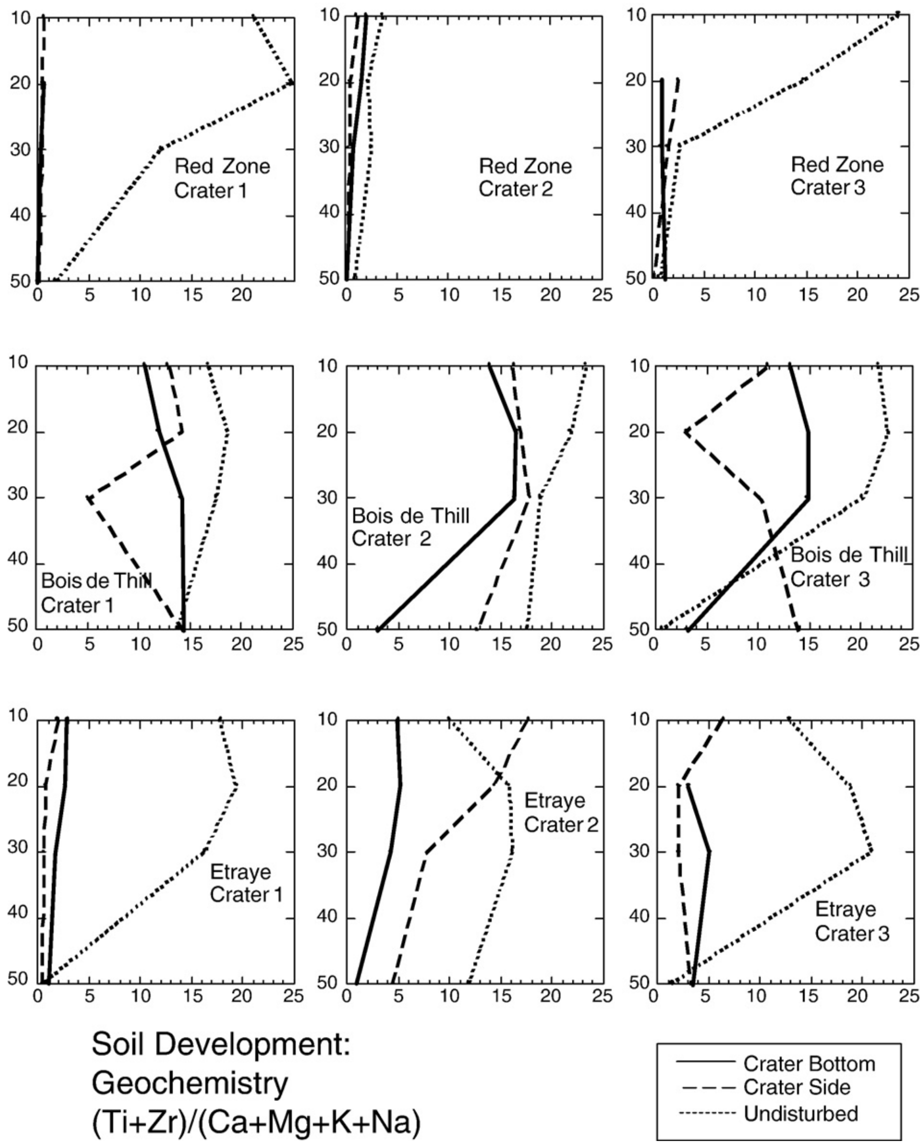

Fig. 7. Soil development on the Verdun battlefield, as indicated by the pedon ratio [(Ti+Zr)/(Ca+Mg+K+Na) at 0, 20, 30, and 50 cm.

weathered C horizon material, in crater bottoms. Tongues of humus-rich material, translocated as earthworm fras, penetrate well into fractures within the C horizon, exposing these surfaces to organic acids and accelerating weathering. Clay-enriched weathering rinds are common on the limestone channers there. Without earthworm activity and bioturbation, crater bottoms would have thicker litter layers (O horizons) and minimal weathering (Schaetzl, 1990).

To summarize, two suites of processes – bioturbation and those associated with the gravitational energy of water – have quickly shaped the course of soil development within the crater bottom soils and led to perhaps more rapid post-disturbance pedogenesis than would otherwise have occurred.

4.5. Divergence in soilscape evolution

The artillery explosions of the battle of Verdun have altered the surface of the battlefield (Fig. 2) to a level where soil development processes vary mainly according to changes in the meso and microtopography. In essence, the Verdun battlefield contains soil spatial patterns and processes that differ from the surrounding landscape it has been set off on a different path of soil evolutionary development (Phillips, 1999, 2001). Now, 88 years later, the spatial patterns of soil development are more complex, and many pedons have progressed onto a different pedogenic pathway. Processes such as littering, humification, leaching, lessivage and weathering, which dominated the pre-War soil landscape, have been changed in intensity and pattern as influenced by crater microtopography. Even the human influence has been largely reduced. Agricultural villages prior to the battle formed a dense patchwork of human habitation patterns, only to be pulverized into a smear on the landscape during the course of the battle. Today all that remains are millions of artillery craters and countless unexploded munitions beneath the surface. A former village may be recognized in the forest by a few bricks poking out from the soil surface while what was once agricultural land is now covered with trees. In this regard, one could say with irony that this particular

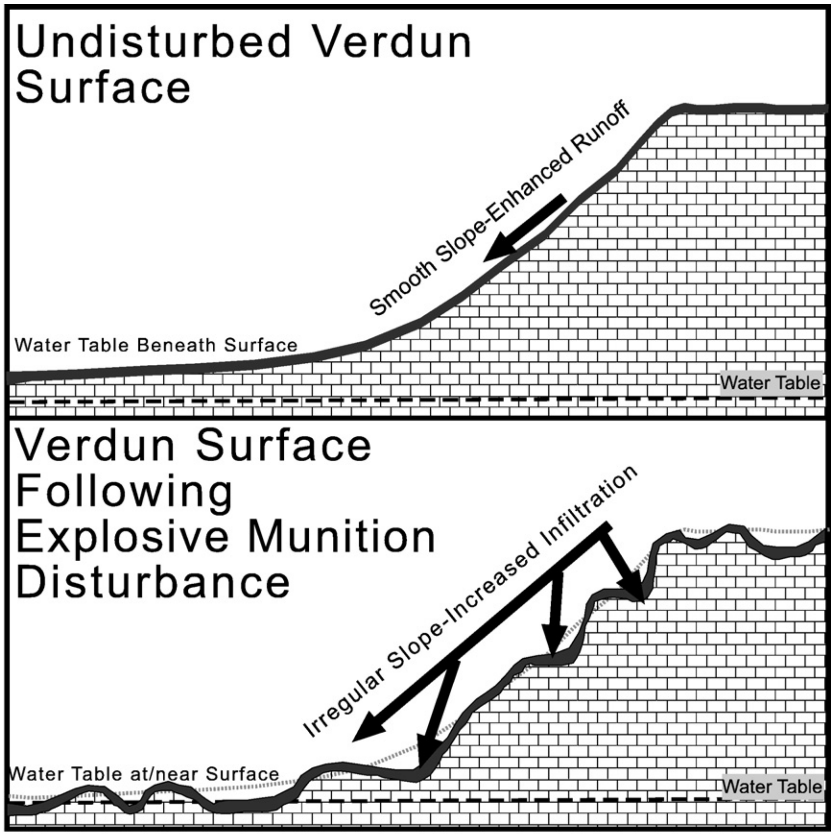

Fig. 8. Generalized diagram illustrating the effects of cratering on slope hydrology at the Verdun battlefield, France.

disturbance has allowed the landscape to revert back to the forested landscape it once was.

Besides changes in the spatial *pattern* of pedogenesis due to crater microtopography, the actual types and intensities of soil and geomorphic processes have also been changed, e.g., Liechty et al. (1997) and Phillips and Marion (2006). Comparatively smooth slopes that foster surface runoff are now pocked with craters that range in size from several meters across and 1–2 m deep, to craters that are 15 m in diameter with depths exceeding 10 m. These changes have had major effects on the surface and subsurface hydrology, and concomitantly, soil development rates (Fig. 8). Pedogenesis is now *enhanced* on ridge tops in crater bottoms due to the increased infiltration of water and organic matter contributions (Runge, 1973; Schaetzl, 1990). However, in locations where large hummocks divide the craters, the hummocks shed water and litter, and soil development is slowed (Schaetzl, 1990). In locations where perched water tables are prone to occur, or along some of the lower elevations in the valleys, many of the crater bottoms are below the water table for a significant portion of the year. Wetness here impedes some of the pre-war processes of soil development, but allow for the introduction of new pedogenic processes, e.g., gleyzation, or the strengthening of the same in preferred sites.

5. Conclusions

The Verdun, France battlefield provides an excellent opportunity to examine the effects of anthropogenic disturbance on soil development patterns and processes. The millions of artillery craters on the Verdun battlefield have changed the area's surface hydrology, water table characteristics, and soil development processes and rates. Our data show how vital it is that soils, in addition to vegetation, be used as surrogates and indicators of landscape recovery. Examining soil development rates and the amount of cratering on the Verdun battlefield provides a better assessment of the true resilience and stability of this landscape. While other research has examined soil development using these parameters on other previously disturbed surfaces, this study is novel in that it examines the development of a soil disturbed extensively via anthropogenic activities, 88 years after the initial disturbance took place.

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