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ASSESSING LANDSCAPE DISTURBANCE AND RECOVERY ACROSS A WWI BATTLEFIELD: VERDUN, FRANCE

By

Joseph Pierre Hupy

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ABSTRACT

ASSESSING LANDSCAPE DISTURBANCE AND RECOVERY ACROSS A WWI BATTLEFIELD: VERDUN, FRANCE

By

Joseph Pierre Hupy

Warfare and the physical environment have always shared a close and interconnected relationship. While a large body of literature examines the ability of the physical environment to influence battle outcomes, a limited degree of research explores the inverse relationship, that is, the various effects of warfare <u>upon</u> the environment. The destruction associated with modern warfare is particularly catastrophic due to the extent, magnitude, and duration of contemporary wars. These large magnitude disturbances radically alter the shape of the landscape, limiting the ability of the landscape to revert back to its original state. By pursuing two research objectives, this dissertation research examines landscape disturbance and recovery across the World War I battlefield of Verdun, France. The **first research objective** was to c*haracterize the varying magnitudes of disturbance*. Five study sites were surveyed that best reflected the varying degrees of disturbance, while maintaining similar environmental characteristics, e.g., bedrock, soil type, and topographic position. Disturbance magnitude was determined by counting craters and measuring their dimensional attributes in two quarter hectare plots at each of the five study sites. Additionally, a

was performed at each of the five study sites. The microtopographic survey recorded changes in elevation to the nearest centimeter at 0.5 meter intervals along 50 meter transects. The **second research objective** was to *characterize, describe, and explain soil development* within the disturbances created by explosive munitions. This objective is based primarily on parameters associated with soil development data. Soil development is ascertained by examining the degree of leaching of various cations from the soil profile and the character/amount of organic matter that has accumulated to form the O and A horizons.

This study provides insight into the ability of a landscape to recover following a catastrophic anthropogenic disturbance. Given the controversy surrounding the environmental implications of modern military operations around the world, via both training and actual combat, it is important to examine the impact military disturbances exert on the landscape. Additionally, humans are increasingly reshaping the face of the earth through activities such as mining, logging, intensive agriculture, and warfare. An understanding of landscape recovery through the holistic approach of studying geomorphic, soil, and bio-ecologic factors will help to better manage and restore severely disturbed landscapes in the future. Such work serves to provide society with a better understanding of how and to what degree landscapes recover, following a catastrophic anthropogenic disturbance such as war.

To the animals, turd burglar and fur

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Acknowledgements are like making wedding plans – inevitably somebody gets left out by accident (or intentionally), feelings are hurt, and somebody crawls into a corner sucking their thumb. Needless to say, I hope to avoid this by listing as many names I can without causing offense. To further cover my aft, I will try not to place too much ranking on these acknowledgements. Of course the names I list first will be the ones that were most involved with the ranking scheme dropping off after the list becomes a lugubrious list of names. I say all this because the only people who generally read these types of works are those listed in the acknowledgements anyways. So here goes…

I would first like to thank my committee chair and advisor, Randy Schaetzl, for it was he who put up with me these past 4 ½ years. This involved keeping me on steady course; dealing with my research proposal, grant proposal, and research award proposals; editing my dissertation drafts; accompanying me to France; not to mention dealing with all the other headaches associated with having a PhD student. Right about now, I also need to acknowledge my extremely amazing wife, (and fellow graduate student also finishing up her work) Christina, for dealing with any frustrations I spewed concerning my advisor (see above), stroking my ego, and being the best help ever in France. Back to the committee. I want to thank all the other members of my research committee, Alan Arbogast, Antoinette Winkler-Prins, and David Rothstein. They all provided valuable assistance. I should mention that each committee member had their niche in regard to advice and interest in this project. It was AWP's Human-Environment that provided the seed for this project. The paper I wrote in that class, which seems so long ago, turned into the monstrosity that you the reader, are about to read. The inspiration Antoinette in that class, Al's interest in military history, and input from other committee members really turned this into what it is. Alan even accompanied me to France – thank you.

Many others helped along the way as well, providing emotional, logistic, monetary, and technical support. First, I will dispense with the monetary support thank-you's. The majority of this work was providing by a generous National Science Foundation Dissertation Improvement Grant. I was also helped along the way by the Geography Department at Michigan State University with Graduate Office Fellowship Funds. I also want to thank Lawrence and Majorie Sommers for their research award and Kenneth E. Corey for also providing me the ability to compete for research dollars. I would also like to thank the Geomorphology Specialty Group for their financial support in the form of a competitive research award. Finally, I want to once again thank Randy and my wife for helping me along the way with funds.

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French who I encountered during my research; they were all helpful beyond what words can convey. I only wish that Americans would treat any visiting French the same.

Inevitably, I have forgotten to mention by name some great contributor. For this I apologize and can only hope my oversight is pointed out so I can thank you in person. I will end by thanking the fates for bringing me to this point in life.

PREFACE

After walking upon a battlefield day after day pocked with literally millions of craters, I sometimes was jaded by the ultimate power that created the destruction surrounding me. I forgot I was in a location that epitomized what the technology of the industrial age was capable of rendering to humans and the environment. Occasionally my objectivity would dim when recording the presence of a piece of human remains, an unexploded ordinance, or some other relict of war. At those moments, I would once again realize that I was standing in a location that was literally a meat grinder, an inferno, and hell on earth – all rolled into one. Sometimes, at these moments, I would gaze at the trench remains dotted with craters, at the bits of barbed wire, the occasional shell peeking out from beneath the 88 year burial, the rare bone fragments, and realize what it meant when the infantry slogging to the front muttered they were entering 'the furnace'. How, I would wonder, did the people in this situation even deal for a day crawling through muddy water filled craters in a cacophony of artillery blasts. I suppose they did it for love of country, believing they were making the sacrifice so their sons and daughters wouldn't have to experience what they did. Unfortunately, those wishes did not come true and the world is currently experiencing more armed conflicts than at any time in the 20th century.

I state this not as an opposition to the military, military endeavors, or to armed conflict. In fact, I am a staunch supporter of the military and highly admirer those who give a substantial part of their lives so I can sit in comfort and write this. I am a realist and realize that sometimes armed conflict does ultimately stem from a terminal ending in political and diplomatic circumstances. I have written this dissertation and maintain an interest in military geography because I want to record what happened and the magnitude of what occurred in the past.

The battle of Verdun is just one of many battles that points to me what a fine veneer covers our 'civilized world'. War is considered a bad word in our society, but we (and that does include me) are all fascinated by it. We seem to live in a world now that pays lip service in homage to those who fought while our nations youth make a mockery of those who have died. Video games such as *Black Hawk Down* recreate the violent deaths of U.S. soldiers whose loved ones must anguish over those memories every time the game is seen at a local Wal Mart or Best Buy. Movies like *Saving Private Ryan* and *Band of Brothers* may illustrate the horrors of war, but it seems all too convenient that the scenes with the most gore are played over and over again on DVD players in the comfort of our living rooms because, in the words of some, "the sound effects are cool."

We are now involved with two separate conflicts in two separate countries (Afghanistan and Iraq). In our bumper sticker society, supporting the war merely means placing a yellow ribbon, or even more recent, a ribbon bespangled with red, white, and blue on the back of our vehicles – sometimes even three or four ribbons will indicate highly patriotic individuals. I can only hope that my research will place an awakening in individuals that the effects of war are far reaching, beyond what, 24 hour news, movies, and video games present.

To dedicate this dissertation to the men who fought or as a wish to end armed conflict would be cheap at best. I only wish to remind people that a study like this examines the battlefield well after loved ones died in agony within a lonely mud slicked crater on a far away battlefield. I encourage everyone to continue with research examining the effects of war on humans and the environment so hopefully war can be remembered exactly how it was and is, not as a video game or movie.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES*

*Images in this dissertation are presented in color

Introduction

In December of 2004, coastal areas in the eastern Indian Ocean were devastated by a massive tsunami, which had been triggered by an offshore earthquake. Entire cities were leveled, coastlines changed, and coastal estuaries altered beneath tons of sediment. Whether it is a tsunami, a volcanic eruption, flood, or forest fire, large natural disturbances like these continually shape the physical environment. Although natural disturbances are capable of rendering massive changes upon the physical environment, humans often ignore one of the largest contributing factors in landscape change due to disturbance – ourselves.

From its very beginnings, the discipline of Geography has placed a great amount of emphasis upon the interactions humans share with their physical environment (Golledge 2002; Livingston 1992; Marsh 1965[1864]; Sauer 1925). For the greater part of its past, the majority of works stemming from the discipline of geography have been on the strong influence that the surrounding physical environment places on human activities and their cultural patterns. This form of research came collectively to be known as *environmental determinism* and was pursued in earnest until at least midway through the 20th century (Sauer 1956). In the 1950's, the geographer Carl Sauer (1956) introduced the concept of cultural landscapes by listing the ways humans *can influence their physical environment.* Sauer contended that, although humans are indeed influenced by their surrounding environment, they also are capable of rendering changes on that very environment through everyday events, including catastrophic ones. Among human activities such as logging, mining, and agriculture, Sauer also listed war as an agent of change upon the physical environment. War acts as an agent of landscape change by causing disturbances of differing magnitudes and type. War is a unique form of landscape disturbance in that it is often larger in magnitude and size than other forms of natural disturbance. War is also unique as an anthropogenic (human) agent of change because of its capability to render such widespread destruction over large areas in such short periods of time (Westing 1980). Despite the magnitude of landscape disturbance associated with modern warfare, however, it continues to be overlooked as a significant form of anthropogenic disturbance (Bazzaz 1983).

One subfield of the field of Geography, *Military Geography,* has a history similar to the broader field of Geography in that, until recently, it has mainly focused on the effects of the physical environment upon the outcome of battle and/or military campaigns (O'Sullivan 1991; Peltier and Pearcy 1966; Winters et al. 1998). Whereas it is important to examine how the physical environment has influenced past military operations, along with studying how to cope with the physical environment in future military campaigns, it is also important to examine the converse, i.e. how and where military operations have *had an effect upon the physical environment.* An extended examination of this relationship - between battle and the environment – has the potential to expand the subfield of military geography into new and exiting directions.

Besides expanding military geography beyond its traditional format, studying the impact of military activities upon the physical landscape is a topic that necessitates attention, given the current circumstances surrounding the military and its increased interactions with the general public. Environmental watchdog organizations such as the Sierra Club and Greenpeace, as well as the Environmental Protection Agency (EPA), all expect the military to maintain a high level of environmental stewardship in its operations, during both peace and war (King 2001). Although military land holdings remain among the largest in regard to public land holdings, the amount of training facilities available to the military is a limited and finite resource. Increasing civilian encroachment upon military training grounds, in addition to advances in technology requiring an increasing amount of space, call for proper environmental management of these facilities. In recent years, the military has done an excellent job managing its current training facilities; a number of studies have focused on the effects of military training operations upon the landscape (Gatto, Halvorson, and McCool 2001; Nichols and Bierman 2001; Prose and Metzger 1985; Albertson 2001). However, these studies have focused mainly on the effects of heavy vehicle traffic upon soil surfaces and not upon the many other effects of military actions, including those of explosive munitions on landscapes.

When searching for areas to study, there exists no shortage of battlefields associated with the many wars and conflicts of the 20^{th} century (King 2001). Many landscapes affected by war still show battle scars. Although these areas may now be revegetated, the soils and surfaces below may remain dramatically altered. For example, North African deserts still exhibit craters and tank tracks from WWII (Westing 1980). In Vietnam, the flight paths of B-52 bombing runs can still be seen in the form of rows of bomb craters - now used as rice paddies by Vietnamse farmers (Westing and Pfeiffer 1972). Europe's infamous Western Front, which stretched from the English Channel to the Swiss border, can still be reconstructed using the bits of barbed wire, artillery craters, and trenches that sprawl throughout the forests (Webster 1994). Several areas along the Western Front were much more disturbed during WWI than others (Figure 1); the Verdun area of France is one of these areas (Horne 1993). It is pockmarked, even today, with millions of craters (Figure 2). With this background in mind, I present the main *objectives* of this PhD research project, centered on the WWI battlefield of Verdun, France.

Figure 1. World War I aerial reconnaissance photo (1916) of the pock-marked Verdun battlefield. The Meuse River on the left side of the image is approximately 25 m across. Source: Clermont-Ferrard, 1919

Figure 2. A typical example of the Verdun cratered landscape near Fluery, France, in May, 2003 Source: Author's Collection

Research Objectives

In this dissertation research I focus on the effects that warfare exerts upon the physical environment. Although warfare impacts the environment in many different ways, my focus will be on the effect of explosive munitions on the soil landscape (soilscape), i.e. the landscape surface and its meso/micro-topographic characteristics (Hole 1978). The WWI battlefield of Verdun, France was chosen for my research because it retains millions of craters, making it an ideal setting within which to perform this research. This research was performed by addressing two primary research objectives (below).

The magnitude of disturbance, as exemplified by the size and density of craters, varies tremendously across the Verdun battlefield. In some areas of Verdun, craters are spaced tens of meters apart, while in other areas craters are overlapping or separated only by hummocky mounds of earthen material. Therefore, my **first research objective** is to characterize and describe, quantitatively, the varying magnitudes of disturbance across the battlefield. In this first objective, I also intend to examine landscape disturbance, through a survey of artillery crater impacts on the micro and meso topography. Gaining an understanding of the effects of warfare on the landscape is an important focus of this research. Equally important, however, are data that address the long-term *ramifications* of warfare, or the ability of a particular landscape to recover; this is addressed in my second research objective. My **second**

research objective sets out to characterize, describe, and explain soil development in those areas (in particular, artillery craters) disturbed by explosive munitions. This part of the research will address questions that center on landscape change and soil developmental pathways and rates, following these types of disturbances.

This PhD research is important because it (1) examines the ability of a landscape to recover[1] after exposure to a catastrophic anthropogenic disturbance, and (2) permits the application (and comparison) of data on landscape recovery using a unique application of soils data. To date, the majority of research involving landscape recovery following disturbance has relied upon vegetation data. In addition (3), only occasionally in soil geomorphology is the beginning of soil development, i.e. time of disturbance followed by stable conditions, known with this degree of precision, providing a unique laboratory within which to study the above phenomena. The information from this body of research promises to advance current theories in soil development and introduce new concepts in the field of soil geomorphology. Finally, this work promises to expand research in military geography beyond its traditional bounds of "environmental influences on battle."

[1] As the reader may have noted, the Verdun battlefield has not truly 'recovered' in the factual sense of the word. A true recovery would mean that the battlefield has reverted back to the state it was in prior to disturbance. When the word recovery is used in the context of this research, it is used as a measure of how closely the changed landscape has moved toward reverting back to its original state.

Chapter 1

Literature Review

Research in military geography has traditionally focused on the outcomes of battle due to environmental influences (Palka 2000). Surprisingly, very little research has examined the opposite relationship – the effects of battle on the environment. In this review, I will begin with a brief overview of traditional military geography to illustrate the strong degree of interaction war has with the physical environment. The next section will focus on the effects of war on the environment, beginning with ancient warfare and continuing through modern warfare of the 21st century. I will also discuss research that has examined the effects of war on the environment, and discuss what aspects of environmental disturbance this research has failed to address. Chapter 1 concludes with an overview of literature that has examined the issue of landscape disturbance along the lines of the ability of a landscape to recover, focusing on its resilience and stability.

Environmental Influences on Battle

Throughout history, warfare and the physical landscape have shared a close and interconnected relationship (O'Sullivan and Miller 1983; Winters et al. 1998). The outcomes of many battles and campaigns has been influenced, or even preempted, by the physical landscape, by either favoring the winner or hindering the abilities of the loser. Numerous books concerning the philosophy of warfare, such as Sun Tzu's The Art of War (2002) or Clauswitz's On War (1968), attest to the importance of the physical landscape in warfare. For example, in the American Civil War, the outcome of the Battle of Gettysburg was largely determined by the ability of the Union army to take the high ground on seminary ridge (Kiersch and Underwood 1998; Winters et al. 1998). Also, in this battle, Confederate artillery forces took advantage of another component of the physical environment – forest cover - by placing their artillery batteries under the cover of forest surrounding the fields.

Forests and the surrounding landscape have been utilized for centuries by armies to mask their movements and provide cover. Two thousand years ago the Roman poet Cicero wrote, "Woods are an ornament in peace and a fortification in war." Having played a role in battle since ancient times, forested landscapes faced the hardships of war right along with the troops maneuvering in their interior (Demorlaine 1919). It is natural in times of battle for warriors to find the best cover possible and it is only natural for the enemy to attempt to flush them out. Even with all the technological improvements associated with modern warfare, forests continue to be heavily relied on by armies, especially in guerilla warfare. This ensures that forests and the physical landscape will continue to suffer from the adverse effects of warfare.

Soils, another important component of the physical landscape, support the agriculture needed to feed a nations' armies and people.

Depending upon their landscape position and textural composition, they can also affect tactical troop movements. For example, the soils of the Western Front across France constantly were a factor that affected defensive positions and offensive movements (Bailey 2004). In the opening phase of the battle of Verdun, German troop movement was impeded due to the heavy shelling that turned the clayey landscape into a quagmire. The artillery bombardment was meant to soften the French defense but did little to French defenses and only softened the soil surface. Not only does this example illustrate how soils can affect the outcome of military operations, it also shows the unintended consequences of explosive munitions upon the physical environment.

Whereas factors such as terrain and soil often affect military engagements at the tactical level of a given battle, they can also affect armies at the strategic level of an entire military campaign (Winters et al. 1998)[2]. For example, the great German advance across Russia in WWII was halted when Germany's mighty tanks were bogged down by waterlogged soils (Keegan 1993). Much like the heavy shelling on the battlefields of WWI impeding troop movements and destroying a once stable soil surface, the movement of an entire German army across the Russian countryside attests to the impact an army can render upon the landscape. However, until recently, the effects of warfare have been largely ignored by those involved with military geography.

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[2] In terms of geographic scale, strategic levels involve entire military campaigns of large expanses of territory whereas tactical levels involve smaller land area, limited to the extent of the battlefield.

Traditional Military Geography

Since the middle of the 19th century, military geologists and geographers have been employed to make intelligent and strategic use of existing battlefield terrain (Guth 1998). Even today, tactical and strategic terrain analysis, fortifications and tunneling, resource acquisition, defense installations, and field construction and logistics are vital components to the study of military geography (Kiersch and Underwood 1998). Military geologists and geographers provide detailed analyses that contribute to making vital decisions on the battlefield. In addition, military geographers often provide historical analyses of the physical environment and the influence it may have had on the outcomes of military engagements. Geographers have also been employed by the military to recognize spatial patterns in aerial reconnaissance data, such as during the preparation for the Normandy invasion or by recognizing nuclear missiles during the Cuban Missile Crisis (Livingston 1992). They also prepare soldiers for war by teaching them to appreciate the landscape and to read maps more effectively (Doyle and Bennett 2002). Notable works concerning the subfield of military geography have been produced by O'Sullivan (1991; O'Sullivan and Miller 1983) and Peltier and Pearcy (1966).

The concepts surrounding military geography also continue as a strong component in the curriculum of military academies, teaching the drawbacks and failures of previous campaigns to future military officers[3]. A well known example of military geographic research that addresses the failures of a past military campaign was performed by Doyle and Bennett (Doyle and Bennett 1999). The authors examined environmental factors leading to the British failure at Gallipoli in WWI. They determined that a major reason for the catastrophic failure of the invasion centered on enemy forces controlling the high ground and potable water supplies. Overlooked in this study were the effects of the military operation upon the semi-arid environment, some of which can still be seen today.

In their analyses, military geologists and geographers often overlook what happens to the landscape after the battle. In this context, many questions remain unanswered. What happens to the forests when enemy forces bombard troops taking refuge in them? What happens to the stability of a soil after an army of 1,000,000 has trodden over it? What happens to the agricultural landscape after it has been bombed and mined over the course of years of warfare? In the following section, I will address these questions through a brief history that covers the effects of war on the environment. I will also discuss the limited amount of research that has brushed upon the impacts of war upon the environment and the dearth of research concerning post-battle landscape changes.

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[3] One of the first two instructors employed by the USMA at West Point was, in a modern sense, a geographer appointed to teach field sketching.

Warfare and its Effects on the Environment

Warfare is, by its very nature, an inherently destructive activity. Not only are the weapons associated with warfare directly responsible for environmental disturbance, but the activities associated with war can severely tax the physical environment as well. Environmental disturbance occurs when armies intentionally eliminate the cover or resource base of an enemy, or more commonly, as an unintentional consequence associated with the war effort. Based on these premises, environmental disturbances associated with war can be placed into three general categories:

(1) Environmental disturbance and destruction from weaponry.

(2) Direct consumption of resources such as timber, water, and food to support armies.

(3) Indirect consumption of resources by military industrial complexes that supply the war effort.

Throughout history the environment has suffered the consequences, either intentionally or unintentionally, of military actions (Westing 1990). The amount of destruction an army is capable of rendering upon the enemy, as well as the environment, is somewhat limited by the technology of weaponry available (Westing 1994). However, environmental impacts associated with the weapons of war are not limited to modern warfare, as the following sections will show.

Warfare in Antiquity, Up to and Though Pre-Modern Warfare

Fire and other incendiary devices were, arguably, the first weapons capable of rendering widespread environmental destruction (Lumsden 1975). Fire has long been employed by armies to drive out enemy forces taking cover in forests, swamps, or other forms of natural cover (Westing 1980). Armies could take advantage of prevailing winds by setting fire to an area upwind from an enemy, thereby creating confusion and fear and smoking them out of their place of refuge. One account from a Roman general in the 1st century B.C. describes a massive forest fire that burned every bit of ground cover and scorched the soil down to the roots of the trees (Westing 1990). This fire was set by Barbarians in the forest attempting to flush the Romans out into the open. The Roman army also employed widespread use of fire in its campaigns within the forests of what is now France and Germany. For the Romans, however, forest destruction was a practice limited against the Barbaric tribes of Europe, in that most uses of incendiary devices in antiquity were aimed at cities, naval fleets, and other fortified positions.

Ancient armies also practiced other forms of deliberate environmental disturbance. The Roman army, known for their pragmatic combat engineering skills, sometimes diverted the course of streams either to cut an army off from its water supply or to redirect the stream through an enemy encampment (Mayor 2003). In some cases, the Romans actually dammed areas upstream from the enemy for a period of time, then deliberately destroyed the dam to create a catastrophic flood designed to wipe out the camp of the opposing army[4]. Sometimes armies set out to destroy the irrigation networks of enemy nations, thereby eliminating their source of water. Such was the case when Ghangis Khan invaded Mesopotamia and destroyed the irrigation networks of the Tigris River (Mayor 2003). Disturbing the water supply of an enemy was, indeed, a common tactic employed by all armies in the ancient world. Although frowned upon in most cases, deliberate poisoning of water sources, such as streams, springs and wells, was not unheard of among many ancient armies.

Disturbance of crops and to the agricultural landscape was also widely employed by armies in antiquity (Mayor 2003). Although not strictly part of the natural environment, agriculture and crops serve as a strong link between the human and physical landscape and continue to be a target of deliberate destruction in military campaigns. Salting an enemy's fields was not uncommon. Perhaps the most well known example of this practice was the salting of Carthaginian fields by the Romans to prevent Carthage from ever becoming a military threat again (Westing 1980).

Deliberate destruction of agriculture and other environmental resources was practiced by the many colonial empires who were vying for control of the fur trade in the New World. One of the better known first

[4] Destruction of dams was employed with great success in WWII and the Korean War. This practice was also implemented in the Second Indochina war, but with limited success.

instances began during the American Revolutionary War when General Washington ordered the fields of the Iroquois Indians, who were allied with the British, razed so only bare earth was left exposed. This practice worked so well that part of U.S. policy during the Indian Wars that spanned the 1800's was elimination of the Native American resources, including destruction of winter sheltering grounds and elimination of once vast herds of buffalo (Westing 1980).

One of the classic examples of material destruction during wartime lies with General William Tecumseh Sherman and his march to the sea in the latter part of the American Civil War (Gates 1965). This march was hailed by northerners as a brilliant military tactic (for cutting off his supply lines, thus 'living off the land') and scorned by the South as one of the cruelest measures ever inflicted upon humankind. In this march, Sherman cut off his supply lines and literally marched across the south all the way to the sea. Troops were sent out to obtain food from the land and destroy everything in their path leaving a massive swath of destruction all the way to the sea.

While ancient and pre-modern armies were deliberately destroying the resource base of opposing armies, they were also consuming resources from those landscapes to support their own war efforts. Trees were cut to supply materials for ships, bows, arrows, and spear shafts; iron and other minerals were mined for weapons and armor; and land was cleared to supply grain. In the age of exploration, the white pine forests along the eastern seaboard of North America were heavily cut in order to supply mast timbers for Her Majesty's navy in Great Britain, while the oak forests of the south were harvested to build the ships.

Before C-rations and preserved food were available, an army on the march had to live off the land it was moving across. An army of several thousand men on the march places severe burdens on the resource base of any given area. That is to say, armies consume massive amounts of food, and before automobiles the horses associated with an army on the march needed pasture grass as well. Nomadic raiders such as Ghanghis Khan and Attila the Hun often were forced to limit the size of their armies based the amount of pasture to support their horses (O'Sullivan and Miller 1983). Not only would consuming these resources ensure the army's ability to continue its military campaign, it would also deprive the enemy of resources needed to fight against the invader. If an army didn't consume the resource base of the area it occupied, then the existing population would often do it for them, by destroying crops and resources of an invading army, thereby depriving the army of its lifeblood through a scorched earth policy. The Romans used this practice widely by burning pasture and crops when the empire was faced with threat of invasion. These practices were not limited to ancient armies and have continued right on to present time; a classic example is Stalin's scorched earth policy on the eastern front against the Germans in WWII[5]. In this vein, perhaps the only difference between ancient and modern warfare is that the methods and techniques only get more sophisticated.

Modern Warfare

In today's world, which is so influenced by modern media, it is easy to imagine that warfare was always a highly destructive epic event capable of widespread destruction. Images rendered by modern cinema that show exploding cannon rounds in 19th century warfare dislodging fountains of earth, and blasting soldiers and trees skyward, inaccurately describe the technological capabilities of warfare at the time. Prior to the 20th century warfare, with some exceptions, was quite limited in its scope and magnitude.

The industrial revolution and technological innovations of the 20th century have changed the face of warfare. Every aspect of modern war is of greater magnitude than that of warfare prior to the industrial age; armies and battlefields are larger, munitions are more powerful, and the disturbances are more widespread. Besides continual advances in explosive munitions technology, modern warfare contributes towards environmental disturbance in many other forms, e.g., heavy vehicle traffic, chemical defoliants, and atmospheric and water pollution.

[5] To deprive the German army of living off the Russian countryside, the Russian army and population were ordered to burn their own villages and fields. Never before or since in history has a country destroyed so much of its own land on an industrial scale, merely to starve the enemy.

Because this dissertation focuses on the effects of explosive munitions upon the landscape, the ensuing review primarily focuses on the history of black powder and explosive munitions, although other forms of environmental disturbance will be briefly mentioned.

History of Munitions

Through the majority of its existence, gunpowder was little more than a chemical propellant used to launch a solid object from the barrel of a gun. From an environmental perspective, the introduction of black powder (the name for the most primitive form of gunpowder) did little to alter the destructive effects associated with military weaponry – that is, until smokeless gunpowder was introduced in the late 19th century. Although its origins are highly contested, it is generally accepted that black powder was developed by the Chinese and first used in firearms in the early 1300's[6] (Partington 1960).

For a significant part of its history in western armies, black powder was mainly used to propel solid objects at high velocities from a barreled device. Projectiles differed little from the solid stones thrown from mechanical catapult devices that had been used previously (Hogg 1987). The mass of the propelled object itself was used to inflict harm upon its given target; its use as a 'bomb' or an explosive munition was fairly

[6] The earliest written account of firearm use in Europe is in an Italian document from 1326, whereas the oldest known Chinese firearm dates back to 1356. Until further evidence is uncovered, the origins of firearms will remain controversial.

limited. Explosive munitions were considered unreliable and dangerous by individuals manning the artillery piece (Hogg 1985). Solid, round shot was delivered from a smoothbore artillery device, employed along the front lines and fired at low trajectories so the round would take erratic bounces into oncoming troops (Bailey 2004; Keegan 1976). Commonly, round shot would be fired until advancing troops were in close proximity; cannons were then loaded with canister fire, which is akin to a large shotgun round. Environmental disturbances associated with solid shot ammunition were limited to divots and burrows formed as the cannon fire hit or missed its mark.

Although these types of artillery devices continued to improve in range and accuracy, it wasn't until 1783 when Lt. Henry Schrapnel invented the spherical bursting shell, filled with many smaller balls, that exploding ammunition was used to any significant degree[7]. The Schrapnel round, as soon came to be known, however, also was considered unreliable since the pre-cut fuse didn't always burst in the intended location (Hogg 1985).

As should now be obvious, the footprint of battle during the early use of artillery left a relatively small mark upon the landscape. Artillery technology right up to the American Civil War (1861-1865) relied upon visual contact with the enemy (O'Sullivan and Miller 1983). The concept

[7] Numbers tallied in 1854 indicate that over 70 percent of all artillery rounds fired in typical battlefield engagements was solid shot projectiles. The remaining percentages were mostly canister fire and other similar 'shot gun' type munitions.

of indirect fire, or firing at an unseen target based upon predetermined coordinates, was in its infancy and considered unreliable. Although artillery pieces were capable of ranges exceeding 2000 meters, gunners nonetheless relied on direct fire by utilizing sights on the artillery pieces (Gudmundsson 1993). Thus, battlefields were small and the impact exerted upon the physical landscape from such engagements was limited due the confined nature of the battlefield.

Introduction of Smokeless Gunpowder and the Age of Modern Warfare

The American Civil War is often thought of as the first 'modern war' because of its highly industrial nature and the implementation of 'total war' tactics (Gates 1965). Whereas many precursors to modern war ominously appeared in this war, including rifled infantry weapons, trench warfare, and rapid troop movements, the war was still waged using first generation warfare tactics (Hammes 2004). The most devastating environmental damage from this war derived from the incredible consumption of resources on both sides to support the war effort. Forests were leveled to produce railroad ties and fuel for railroad transport – a relatively new innovation that allowed rapid deployment of troops and greatly expanded the military campaign theater. Also, coal was mined with abandon to produce the steel needed for the war machine, and hastily dug iron ore mines produced detrimental environmental effects that are visibly apparent, even to the present day (Whisonant 1998).

In addition to the inadvertent destruction associated with resource consumption in this war, the concept of 'total war[8]' also left a massive swath of destruction across the south. However ominous and foreboding were the signs of modern war, European observers returned to their respective countries at the end of the American Civil War with little thought of a revolution in warfare tactics, not fully realizing the full power of industrial warfare and rifled infantry weapons (Bailey 2004).

Armies continued to use weapons with black powder as a propellant for several decades following the American Civil War. Rapid fire, breech loading, and rifled barrel artillery were introduced to compete with the longer range of infantry, but the nature of the black powder propellant made them unreliable and dangerous due to build up of powder residue in the barrel. Then, in the late 19th century, Alfred Nobel introduced the world to smokeless gunpowder, blasting caps, and a new 'safer' form of explosive called Trinitrotoluene, commonly known as TNT (Hogg 1985, 1987; Webster 1996). Shortly after this development, in 1899 the French introduced the highly explosive (HE) form of munition. This artillery shell was filled with highly explosive cordite and fired from a rifled, breech

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[8] In total war, everything is subject to the consequences of war – including civilian populations of belligerent countries. Prior to the concept of 'total war', warfare between western nations was limited to engagements between the armies themselves. Damage to enemy resources and civilian populations was generally frowned upon as 'uncivilized'. However, the practices used in total war would soon become the norm in modern warfare of the 20th century

loading, artillery device. Soon, the British followed with the more explosive melanite and through the use of chemistry the world came to know the possibilities of ever larger and more powerful HE rounds. These explosives, combined with the age of industrialization, ushered in a new form of warfare capable of leveling forests and cratering landscapes beyond recognition.

Although several wars, such as the Franco Prussian, the Russo-Japanese, and the Spanish-American, allowed armies to 'test' and develop munitions that utilized the weapons of modern war, it was not until WWI that these developments were fully implemented at an industrial scale (Bailey 2004; Keegan 1993). In WWI the same concepts associated with the Industrial Age were introduced into the philosophy of war. Instead of armies that numbered in the thousands, a nation needed armies in the millions in order to be a powerful, warring nation state. A nation required a well-built infrastructure and massive industrial complex just to support its massive armies. For example, by several months into the 'Great War' (as WWI would soon be known), it was realized that those nations capable of out producing the other nation would have a distinct edge. Commanders also realized that the days of dashing calvary charges and brightly colored uniforms, used so armies could communicate in the thick smoke of battle, were over; new tactics needed to be implemented.

The extremely long range of rifled infantry weapons and the rapidly firing machine gun forced commanders to take artillery off the front lines after several devastating losses in the beginning stages of WWI[9]. Artillery took up positions in the rear and perfected the art of indirect fire, based on the calls of forward observers. The role of artillery was to heavily shell an area in order to destroy enemy defenses and shatter its morale. Terms such as the "straight barrage", "rolling barrage", "piled up barrage", and "creeping barrage" were coined to refer to curtains of artillery fire placed directly in front of advancing troops to obliterate anything on the surface.

Before WWI, artillery units attached to armies were allotted, at most, 100 rounds per day for combat operations. By the end of the war, artillery units were assigned several hundred rounds per hour[10]. At the start of the war, artillery was seen as an arm to directly support the infantry and wars were won by élan, or courage of the infantry; by the war's end, the mantra of all commanders was, 'Artillery conquers and infantry occupies" (Gudmundsson 1993). Artillery therefore emerged from WWI as the deciding factor in battle (Figure 3).

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[9] Breech loading rifles and rapid firing weapons such as the Gatling Gun were in existence since the American Civil War, but army commandeers were slow to adopt to changes brought about by these weapons, mainly because most countries did not upgrade their arsenals with these weapons until the advent of WWI.

[10] In the age of smooth bore artillery, artillery units often brought one round per gun into battle, siege guns firing more than 5 rounds per day was considered exceptional.

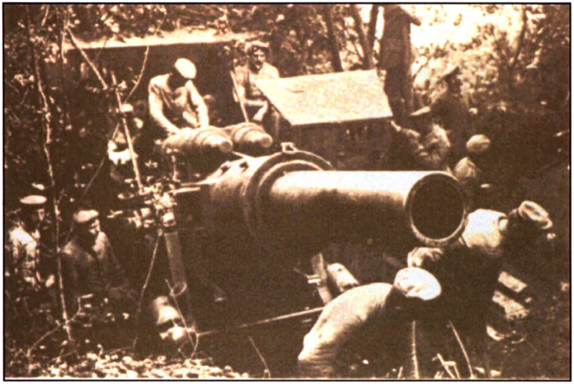

Figure 3. A German 310 mm (10-inch) howitzer at Verdun in June, 1916. The Germans employed several hundred of these guns during the battle, typically concentrating their fire into very small sections of the front. Source: German Bundesarchive

The environmental consequences of this type of warfare obliterated forests and significantly cratered the landscape, thus creating wide swaths of destruction (Figure 4), limited only by the range of artillery which could fire, which was well beyond the visible range of the gunners (Hogg 1987). Perhaps the best known example of this swath of destruction is the Western Front, which was an average of 20 km wide and stretched from the English Channel to the border of Switzerland (Keegan 1998).

Figure 4. Forest and soilscape destruction along Western Front during WWI (1914-1918) Source: Clermont-Ferrard, 1919.

European and American foresters took notice of the destruction wrought by WWI and, by the end of the 'Great War', foresters began to assess the toll exacted on the environment (Graves 1918). This assessment was accomplished primarily by determining forest damage in terms of board feet of lumber lost by: (1) outright destruction, (2) damage due to shrapnel impregnation, and (3) harvest to support the war effort. Several studies (Demorlaine 1919; Graves 1918; Kernan 1945) estimated that 2.5 billion board feet of lumber in French forests had been destroyed during the course of the war. Ridsdale (1916), an American forester attached to the US army, reported that not only did the artillery bombardments reduce forests along the Western Front to splinters, particularly those in France, they also created a cratered landscape that reduced a once stable soil ecosystem into mounds of loose, unconsolidated sediment that was hardly worth calling 'soil'. Veterans of WWI described the landscape after an artillery bombardment as unworldly and like a scene of destruction that is incomprehensible. Ralph Bagnold, an eminent soil physicist and veteran of both WWI and WWII, provided an account of the landscape after an artillery bombardment in his autobiography Sand, Wind, and War. "...On the main Passchendale ridge, whole villages were blown up, woods disappeared, and the courses of streams were changed (Bagnold 1990, p.32)." Beyond description of the horrendous effects to soils and the landscape however, no scientific assessment was made beyond that of estimated losses of trees.

After the brief interest displayed by foresters immediately following WWI, the western front was largely forgotten; humankind was so horrified by the death and destruction associated with this war that it was said to be 'The war to end all wars'. Unfortunately, WWI only set the stage for WWII and barely 20 years after the last shot of WWI, Europe plunged into another round of warfare. In this war however, the damage to the soilscape (at least in the countryside) was much more limited. In the years between, the war's explosive munitions had become much more powerful; the toll exacted on the landscape was, however, minimized due to the fluidity[11] of the front lines. In addition, the majority of artillery and aerial bombardments of WWII were concentrated in urban areas.

In WWII the soil surface may have been spared, but not the forests. Over 100 million acres were directly destroyed through combative activities in French forests alone during WWII (Kernan 1945). Artillery shells were also much improved, with better timing devices designed to explode directly above troops taking cover in foxholes and trenches. Explosions in the forest canopy would not only rain down shrapnel, but also thousands of wood splinters from the exploded trees. In the Pacific campaign, many islands endured days of naval and aerial bombardments to 'soften up' the enemy before the beaches were stormed. Islands such as Tarawa, Iwo Jima, and Attu were subjected to heavy naval and aerial bombardment prior to amphibious infantry operations (Palka 2000).

European forests also underwent heavy exploitation during both WWI and WWII (Kernan 1945; Ridsdale 1919). Wood products were heavily utilized during these wars to construct rail lines, provide posts for barbed wire entanglements, telegraph lines, strengthen trenches, and many other war related activities. During both wars, occupied countries were heavily exploited for their resources in order to supply the war effort. It is estimated that nearly 17 billion board feet of lumber was harvested from the forests of France during WWI (Ridsdale 1919). The cedar tree on the

[11] The weapons associated with WWI such as machine guns and the subsequent heavy reliance favored stagnant defensive positions. It was not until the introduction of the tank and other armored vehicles near the end of WWI that technology allowed the rapid 'blitzkrieg' tactics associated with WWII.

flag of Lebanon is now merely a symbol of what was a once mighty forest, after being obliterated by the Ottoman Empire during WWI to supply fuel for their railways. During WWII, German forces occupying France increased harvesting activity by a full 50% more than French harvesting in times of peace (Kernan 1945). Britain also heavily exploited her forests during both wars and many majestic timbers from protected parks and recreational areas were sacrificed for the war effort (Anonymous 1915).

Following WWII, many individuals in military circles believed that the widespread destruction associated with the two previous wars of the 20th century was a relict of the past. Warfare was seen as approaching a new age; one of rapid movement (likely, over the eastern plains of Europe) and, if it came to it, mutual nuclear devastation. These misconceptions would have been quickly disabused if those same individuals witnessed the magnitude of environmental destruction created by the Second Indochina War, or the Vietnam War as it is referred to in the United States. In WWI and WWII, the damage inflicted upon the forests and soilscape was incidental, in that the damage was a side-effect of the intention to eliminate enemy forces. The Vietnam War differed from previous wars of the 20th century in that destruction of key components of the country's physical environment was a deliberate military strategy (Westing 1976). For example, a major portion of the U.S. war effort in Vietnam was the elimination of forests (Westing 1996; Westing and

Pfeiffer 1972). Deforestation of the dense, tropical selva was done to eliminate cover for enemy troops, provide bases of operation, and to create landing strips for aircraft and to establish landing zones (LZ's) for troops deployed by helicopter (Lewallen 1971).

Three main factors helped contribute to the elimination of Vietnamese forests: (1) explosive munitions, (2) herbicides (Agent Orange), and (3) land clearing operations from specialized bulldozers called 'Rome Plows' (Westing 1971). Although artillery bombardment was heavily utilized in this war, aerial bombardment inflicted damage to the forests and the enemy at a scale never before accomplished. Much of the damage inflicted upon the forests through highly explosive, shrapnel-producing munitions was the same type as seen in previous wars, except that it was accomplished with larger and more effective 500 lb. bombs, typically dropped from B-52 bomber formations (Westing and Stockholm International Peace Research Institute. 1984). These bombs destroyed vegetation outright, tore it open with shrapnel, and left it impregnated with small pieces of shrapnel (Westing and Pfeiffer 1972). US Air Force bombers in this war also widely practiced 'carpet bombing' in which B-52 bombers would fly over and lay down a blanket of bombs into an area thought occupied by enemy forces. The B-52 bombers left wide swaths of disturbance, dotting the Vietnamese landscape with millions of craters (Figure 5). Typically, these bombing runs consisted of 3 to 12 aircraft, each carrying 108 500 lb. bombs. The swath of disturbance created by such missions saturated an area with bombs approximately half a kilometer wide and over 1000 meters long (Orians and Pfeiffer 1970). Conservative estimates place the number of craters left behind from these carpet bombing missions at around 26 million (Westing and Pfeiffer 1972). The effects from these bombing runs can still be seen on the Vietnamese landscape today (Figure 6).

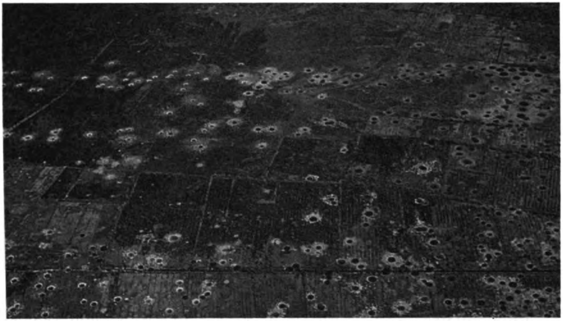

Figure 5. Cratered South Vietnam agricultural fields. The linear pattern of the craters is due to the path of B-52 bombers. Source: Westing, 1972

Carpet bombing by B-52 bombers was not only limited in use to the attempt of exposing the enemy taking cover in the forests, it was also used to destroy large expanses of agricultural land (Westing and Pfeiffer 1972). One soldier remarked on the destruction, as seen from above, "...bombers and artillery pound the [land] into the gray porridge that the green delta land becomes when pulverized by high explosives (Westing 1976, p.18)."

Figure 6. A 500 lb. bomb crater (beneath yellow arrow) in Cat Tien National Park, Vietnam. This area of southern Vietnam was heavily bombed and sprayed with herbicide agents. Date of photo unknown. Source: http://www.geog.ucl.ac.uk/~sdwyer/sites

Figure 7. Aerial view of land clearing operation by Rome ploughs in southern Vietnam. Source: Westing, 1972

Not surprisingly, many of the same activities employed by the U.S. Army to destroy enemy forests were used to destroy enemy agriculture. Herbicidal chemicals were dumped on large expanse of rice paddies while “Rome Ploughs” were used to destroy the dikes associated with rice production (Figure 7). As should now be obvious, in Vietnam, the war against forests and agriculture was as much a component of the overall war effort as was the attrition against the Viet Cong.

Sometimes, specialized aerial bombs were dropped for the singular purpose of clearing a large tract of land in the thick forests of Vietnam. One such bomb frequently employed by the U.S. military during this time was the infamous ‘Daisy Cutter’. In fact, this bomb and others more powerful than this are seeing use in our current wars being fought in

Iraq and Afghanistan. The bomb, about the size of a Volkswagen, is dropped from a C-47 transport plane and drifts to the ground via parachute. It explodes immediately upon contact with the ground. A parachute is employed to reduce the amount of penetration into the ground thereby directing the blast outward instead of into the ground (Westing 1972). In this manner, a large diameter landing zone, about the size of a football field, is carved out of the forest without producing a crater. The cleared area of former forest is then used for troop implant and extraction purposes (Figure 8).

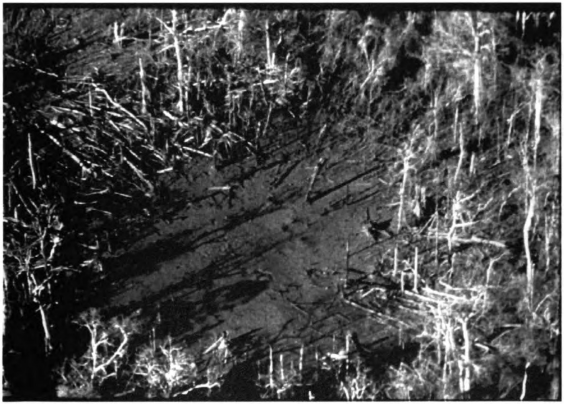

Figure 8. Leveled forest at ground zero following Daisy Cutter bomb explosion. Source: Public domain, http://members.aol.com/samc130/bc130.html

Incendiary bombs were also implemented in Vietnam at larger scale than any previous war (Lumsden 1975). In 1965, 'Operation Sherwood Forest' was implemented as a measure to destroy, through massive forest fire, almost 30,000 hectares of Vietnamese tropical forest (Westing 1976). The results from this operation leveled hundreds of villages and left hillsides scarred to the present day. The U.S. military soon realized the tropical rainforests did not contain enough ground cover nor were they dry enough to sustain large wildfires. Thus, a new strategy was needed to clear large tracts of forests, forcing the military to turn its attention to chemical agents. Herbicides known collectively as agents orange, white, and blue were implemented at an industrial scale with the sole intention of eliminating massive tracts of forest vegetation (Westing 1976; Westing 1977). Unfortunately, the chemicals in these herbicides not only harmed the vegetation they were intended to eliminate (Figure 9), but they had severely harmful effects on the people occupying the forests, e.g., U.S. troops and rural villagers. Anyone familiar with the Vietnam War probably knows of some horror story associated with the herbicide Agent Orange.

Figure 9. Aerial view illustrating effects of herbicide 'agent orange' (upper left portion) on Vietnamese forests. Note additional destruction due to 500 pound bombs. Source: Westing, 1976

As in Europe at the end of WWI, the forests of Vietnam were examined near the end of the war to assess the extent of disturbance (Orians and Pfeiffer 1970; Pfeiffer 1969). After flying over many areas that had just been subjected to an aerial bombardment, foresters reported a landscape that resembled the surface of the moon. It was estimated that 1.65 million hectares of forest had been completely destroyed. In addition, foresters estimated that 4% of the country's forests were so impregnated with shrapnel they had no lumber value whatsoever (Flamm and Cravens 1971).

In addition to forest damage, the impact of warfare on soils is also widespread, though much less studied. Following aerial bombardments in Vietnam, foresters described the Vietnam landscape as a moonscape of craters and scorched dirt. They proposed that after the soil loses its protective forest cover, it may undergo laterization – a process that turns exposed soils into dry, rock-like laterite (Westing and Pfeiffer 1972). Soil disturbance also has implications for the way vegetation and soil respond to changes local water table conditions wrought by disturbance. In some instances, impermeable bedrock and soil layers are breached by cratering, depriving the vegetation of its former source of water. In other instances, cratering exposes the water table and inhibits deep rooting of vegetation occupying that crater, limiting subsequent reforestation.

One of the largest environmental catastrophes of the 20th century, if not the largest, is associated with the Kuwaiti oil fires of the 1991 Persian Gulf War (Figure 10) due to the intentional destruction of oil facilities by Iraqi armies under orders from Sadam Hussein (Husain 1998). Iraqi forces sabotaged about 730 oil wells, 20 collecting centers, and 3 or more oil tankers (Westing 1994). These fires polluted the atmosphere, contaminated the soil and underwater groundwater resources, and decimated millions of acres of shoreline habitat (El-Baz 1992). More than 60 million barrels of oil were released on land and into the ocean. Massive amounts of atmospheric pollution resulted from the over 700 burning oil wells. Soil samples taken in a 1000 km radius from the disaster site contained higher than normal amounts of organic carbon in their upper horizons, probably from soot that had fallen from the atmosphere. Downwind up to 6 km from the flaming plumes, two inches of oil covered the surface due to the fallout of heavy oil droplets (Husain 1998). Several studies have also examined the effects of heavy vehicle traffic upon the desert soils of Kuwait and found that dust storms increased in magnitude and occurrence following these disturbances (Al and Beg 1998; El 1992, 1994; El, Al, and Al 1994; El and Al 1996).

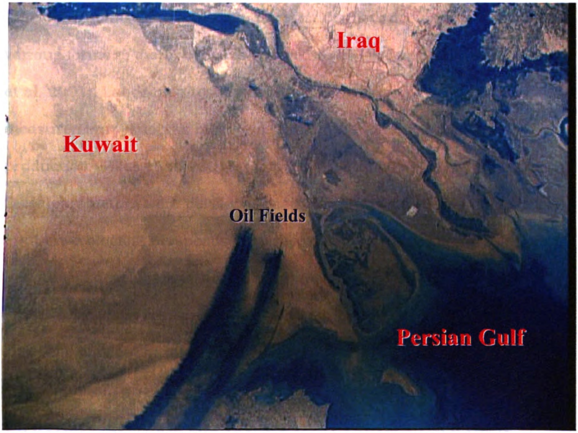

Figure 10. Smoke drifting to the southwestfrom the burning oil fields to the north of Kuwait City in April, 1991. Source: Public domain, (http://science.ksc.nasa.gov/mirrors/images/html/STS37.htm)

As the reader may have noted by now, environmental disturbance is a constantly recurring theme of war. It started in antiquity and has continued right up to present time. The only aspect of wartime that has changed is that weapons and armies become ever capable of creating disturbances that continue to increase in magnitude, type, and perhaps, frequency.

Landscape Resilience and Stability

The ability of a landscape to resist disturbance and to recover from various forms of disturbance is referred to as landscape resilience (Miles et al. 2001). Landscape resilience is based on various bio-ecologic measurements, such as biodiversity, biomass, and net primary production (Miles et al. 2001; Usher 2001; Wali 1999). However, most of these parameters were developed mainly to measure landscape recovery from an ecological perspective. Surface instability and degradation, as well as soil development, are often ignored, although they also reflect overall landscape resilience. Geomorphologists have therefore expanded upon the concept of landscape resilience by including geomorphic factors into a factor called landscape sensitivity; i.e. the stability vs instability of a landscape (Brunsden and Thornes 1979). For example, a stable landscape contains surfaces that do not easily erode and recover quickly from disturbances that cause erosion/burial (Usher 2001). Under stable conditions, soil formation can proceed relatively uninterruptedly. Thus, soils are often used as indicators of stable conditions (Brunsden 2001). Most soil-related sensitivity applications, however, have been in long-term landscape studies, such as research involving Quaternary environments (Balek 2002; Dan and Yaalon 1968; Parsons, Balster, and Ness 1970), because they generally take a long time to develop and therefore reflect long periods of landscape stability (Schaetzl, Barrett, and Winkler 1994).

Because soils indicate long-term landscape stability, they have often been ignored in short-term landscape recovery studies (Thomas 2001). Indeed, only a limited amount of research has examined soil properties as an indicator of short-term recovery in under both natural and human forms of disturbance (Indorante and Jansen 1984). And studies that have examined soil development after disturbance usually focus on disturbance by commercial activities, e.g., mining or logging operations (Lebedeva and Tonkonogov 1995; McPherson and Timmer 2002; Roberts et al. 1988; Wali 1999). With regard to disturbance from military activities, a few limited studies have examined the ability of a soil surface to recover after being subjected to tank and other forms of heavy military vehicle traffic (El-Baz et al. 1993; Gatto, Halvorson, and McCool 2001; Lebedeva and Tonkonogov 1995; McPherson and Timmer 2002; Nichols and Bierman 2001; Prose and Metzger 1985; Roberts et al. 1988; Wali 1999). Taken together, this body of research has clearly shown that soils, in conjunction with bio-ecologic factors, can be used to assess anthropogenic environmental impacts, along with the spatial variations of recovery, on disturbed landscapes (Brunsden 2001; Wali 1999).

The above review also shows the dearth of previous research regarding military impacts on the environment. Research involving landscape disturbance due explosive munitions is limited to immediate assessments of vegetation, with only brief mention of the soil. More work is needed beyond disturbance to soil surfaces from military vehicles. My goal is to expand upon this previous limited body of research by utilizing soil parameters to examine landscapes affected by the explosive munitions associated with war.

Theoretical Concepts Surrounding Human Impact on Soil Formation Processes

In his 1941 work, *The Factors of Soil Formation*, Hans Jenny mentioned humans as implicitly contained within the biotic (o_h) soil forming factor (Jenny 1941). Jenny went on to discuss how humans have greatly changed many of the environments in which they live. He mentions how we have changed the surface of the earth in many ways to suit our needs. He discussed in detail the degree of soil transformation that has gone on in the Great Plains due to human influence. Despite the detail of discussion, Jenny did not formally detail the human component into his five soil forming factors.

The work of Jenny was cited several times after this during the 1950's and a piece by Simonson (1959) compared soils under natural vs. culturally influenced conditions. Although Simonson compared soils under cultural vs. natural environments, he never directly addressed how humans play into soil formation theory. During this decade, Jacks (1962) also wrote of humans as a fertility agent upon the land. Jacks praised the work of humans and dismissed the reports of humans as a pure exploiter of soils. Jacks pointed out how, through human additions, many soils in forested areas, especially in Europe, are now more fertile than ever before. Today, the reader may conclude that both these authors implicitly included humans into the factors of soil formation, but neither author ever addressed the theory.

In 1965, Bidwell and Hole published a paper that directly addressed the human component in soil forming theory (Bidwell and Hole 1965). They proposed that humans, unlike other living organisms, contain a cultural component along with a genetic component. Therefore, different cultures will exert different influences on soil formation. They also addressed the cultural influence of humans on each of the five soil forming factors. Examples of human influence, both positive and negative, were cited for each of the five soil forming factors.

Shortly after the Bidwell and Hole 1965 article, Yalon and Yaron (1966) published a work that once again attempted to place humans within existing soil formation theories. These authors recognized the human influence on each of the five soil forming factors, but disagreed with the way in which humans are treated as a separate factor or included within the biotic soil forming factor. Yalon and Yaron proposed that when human influence is involved, then the theory of metapedogenesis should be applied. This means that natural pedogenic conditions have stopped and new influences are now applied to the soil. Essentially, the soil forming clock is stopped with human influence and a new phase of development then occurs.

After this brief stint of incorporating humans into the theory of soil formation, several decades went by before the issue of human influence on soil formation was once again focused upon. Hans Jenny wrote another book in 1980 that was much a follow up on is 1941 classic (Jenny 1980). In his new work, Jenny went into much more detail concerning humans as a factor in soil formation. Then, in 1991, Amundson and Jenny produced a work that took into account the Bidwell and Hole article and the Yalon and Yaron article (Amundson and Jenny 1991). In this work, the authors acknowledged that humans have indeed influenced each of the soil forming factors. The authors maintained that humans should be considered as having a cultural element and should be considered a separate soil factor. They even suggested an anthroposequence concept and that these can be negative after human occupation of an area ceases. They cited castles in Europe as examples. Perhaps the most important point of this piece was that humans alter pedogenic processes but are not in themselves pedogenic agents. Anthropogenic influence only goes as far to change the path of natural processes. In other words, the five natural soil forming processes still create the soil but the human hand alters the path or speed of the process.

Today, an ever growing body of research is developing theories concerning the human element as a factor in soil formation. Much of this research is occurring in Europe (Grieve 2001), particularly Germany (Beyer 2001; Mueser 2001). Current literature focuses more on the anthrosol concept (Lebedeva 1995). This is a newly proposed soil order that owes its origins to humans, predominately through creation by human parent material. Current Anthrosol research focuses on urban areas where the parent material of many soils derives from human by-products such as mine tailings, garbage dumps, and industrial fallout. Research concerning the taxonomy of Anthrosols has also been addressed along with the methodology of mapping such soils (Schleuss 1998; McIntyre 1999).

Although a good deal of progress has been made to incorporate the human influence into soil formation, there is still a great deal that needs to be adequately addressed. This brief review of the literature indicates that research concerning 'natural' soil forming factors far outweighs research involving human influence on soil formation. The soil forming theories have been placed into the literature, now it is up to pedologists to test the theories and perform more research involving soils influenced by humans.

The best way to better conceptualize the human factor is through more research in the fields of pedology and soil geomorphology. Soil scientists will readily admit that finding extensive areas of 'natural' soils is becoming more and more difficult. Finding an unaltered prairie soil is next to impossible yet research continues to study soils in the 'ideal' state. The first step in conceptualizing the human factor within soil formation is to recognize that a great deal of soil has been altered by humans and the time has come to document these soils. Increasing the amount of research in this field will not be an easy task. More work is required involving how anthropogenically influenced soils tie into the physical landscape. My work on the Verdun battlefield will contribute towards this body of research.

Conclusions

In conclusion, a great deal of geographic literature has focused on the ways in which the physical environment has altered the outcome of military campaigns (Doyle and Bennett 2002; Demorlaine 1919; Guth 1998; Kiersch and Underwood 1998; Winters et al. 1998). However, very little research has focused on the impacts of war upon the environment. This research fits within a new avenue of research within the realm of geomorphology by studying the impact of warfare upon the environment. In addition, the contextual findings of this research may assist in enhanced management and maintenance of other anthropogenically disturbed landscapes, such as those areas subjected to mining, logging, and detrimental agricultural practices. Soil geomorphic research has made great advances in landscape recovery following disturbance events, although more research is needed to address the impacts of humans on the physical environment (Beyer et al. 2001; Grieve 2001). To address these issues, I chose to study the WWI battlefield of Verdun, France.

Chapter 3

Study Area

The battle of Verdun remains one of the most intense battles fought between two belligerent nations in all of history. Verdun remains a textbook example of a battle of attrition. Both nations, Germany and France, expended millions of rounds of ammunition and sent hundreds of thousands of men to their death. Although the scars of battle still remain scattered on the European Western Front, the Verdun battlefield remains one of the better documented, most scarred and unaltered battlefields, since WWI ended on November 11, 1918.

Historical Context

In regard to traditional military geography, the Verdun area presented Germany with some of the worst physical conditions to launch an offensive operation: heavy and prolonged precipitation, long, cold winters, steep, east facing escarpments, and clayey soils that bogged down equipment and soldiers (Winters et al. 1998). Knowing of the area's physical geography, one may wonder why the Germans ever launched an offensive in such an unsuitable area, over all the other possible locations along the Western Front. Therefore, it is important to explain the factors leading up to the battle as well as a brief history of the battle.

By 1915 WWI, which began with dashing calvary charges and brightly colored uniforms, had succumbed to the reality of technology

(Horne 1993). The central and allied powers were locked in a stalemate along the Western Front (Figure 11), from the English Channel to the border of Switzerland (Brown 1999). Offensive movements were extremely limited due to extensive trench networks and the deadly efficiency of machine guns. It seemed that no matter what offensive action was taken, breakthrough was impossible; stalemate had become the reality of this war.

Late in 1915, however, the German high command came up with a contingency plan that was designed to break the stalemate and ultimately knock France out of the war (Holstein 2002). The plan was unconventional in that it contained no strategic objectives and was designed merely to break the will of France to fight, via a battle of attrition by 'bleeding her to death'. Germany reasoned that by eliminating France from the war, Russia could be defeated in the East, and then Germany could turn around and conquer her true enemy in the west - England. In essence, Germany wanted to 'eliminate the sword from England's right hand' by demoralizing France to the point of surrender and ultimate defeat. Germany chose the Verdun region to launch the offensive because they knew it to be a highly symbolic French region and they (France) would throw everything they had into defending it.

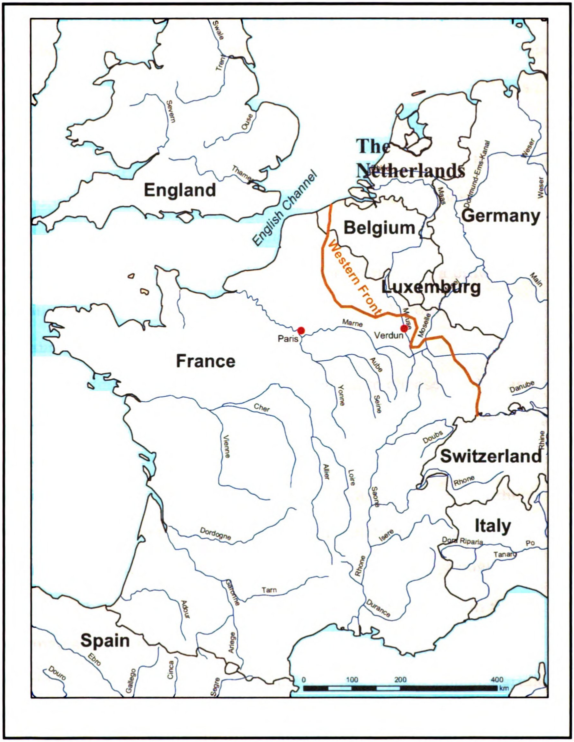

Figure 11. The political geography of modern Europe in relation to Europe's Western Front in 1916. Source: ESRI data products, 2005.

The strategy behind the decision of the German high command was based on French pride and patriotism. During the Franco-Prussian war of 1871, France suffered a humiliating defeat at Sedan and was forced to cede control of its Alsace-Lorraine province to Germany (Ousby 2002). Verdun suddenly became part of the French frontier, bordering newly acquired German territory. France, to protect her borders from further losses, set up a massive ring of forts to protect the region. The area had thus become a symbol of pride for France and a bulwark against German invasion. Thus, WWI began with Verdun located in proximity to border of Germany.

An additional incentive for the Germans to choose Verdun as a launching point for a major offensive operation centered on supply line logistics. France had few roads to supply the front and these roads could easily be destroyed (and were) by well-placed artillery, whereas the German side of the front was blessed with a plethora of supply lines to feed the offensive (Clermont-Ferrard 1919; Winters et al. 1998).

The battle of Verdun began on February 21st, 1916 with the German army launching a massive artillery barrage in the Bois de Caures, the center of the Verdun salient (Figure 12). The opening artillery barrage lasted for two days and was the largest artillery bombardment of the war to that point (Martin 2001). At first, the Germans made large offensive gains, but eventually this battle, like the war itself, became locked in stalemate with both sides pouring hundreds of thousands of men into a futile struggle (Brown 1999). Both sides relied heavily upon artillery to break the morale of the enemy and 'soften up' the other side for an offensive effort to retake a fort, pillbox, trench, ridge or high point on the battlefield. Objectives changed hands daily, with fresh craters forming within old craters and trenches re-dug into trenches excavated only hours before (Cowley 2004). Ironically, the same artillery barrages designed to soften up the defense only created a quagmire for the offensive, leading many troops to drown in the very craters their own side created to help them. For nearly a year, this exchange of artillery continued to pulverize the landscape into what many soldiers described as 'something from another world' (Bagnold 1990) or what pilots flying above would relate to as 'the surface of the moon' (Horne 1993).

In July of 1916, the Germans offensive drive began to slow down due to the need to redirect men supplies towards staving off the allied offensive at the Somme, another atrocious battle of WWI. Soon thereafter, the French began to push the Germans back towards their original lines with the usage of their own heavy artillery. The battle officially ended when the French regained territory lost to them during offensive operations in October, 1916. Thereafter the Germans withdrew to prepared defensive positions and the area remained fairly quiet until the Americans began offensive operations to push the Germans out late in 1918.

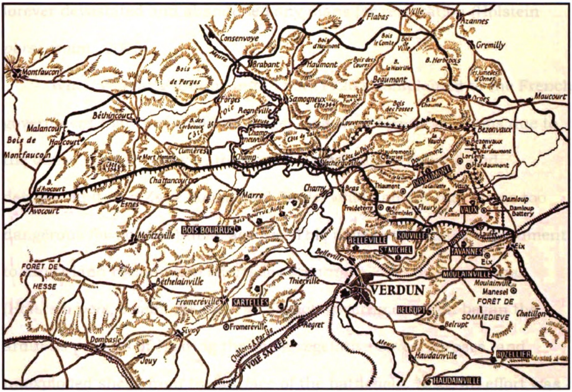

Figure 12. Verdun and surrounding villages, circa 1916. The lines on the map represent the movement of the front lines through the course of the battle. The heaviest fighting occurred in the center of the battlefield near the forts of Vaux, Douaumont, and Souville. Correspondingly, this is where the heaviest landscape disturbance occurred. Source: Clermont-Ferrard, 1919

After WWI, the Verdun battlefield was abandoned; many bodies were left to decay and the remnants of war were strewn everywhere. Large expanses of agricultural land were never replowed due to the tens of millions of craters and unexploded shells lying on or just beneath the surface. Many of the villages that once dotted the region were never rebuilt. Eventually the barren, cratered surface became covered with a thick mass of shrubby vegetation. French officials believed the area was forever devastated and abandoned any plans for restoration (Holstein *pers. comm.*. 2003).

When veterans' groups in the mid-1920's complained to the French government that they could no longer visit their former positions due to the dense vegetative cover, the government bought the land and designated it as a *Zone Rouge* (Red Zone), which meant that it was too dangerous for normal public access. This policy allowed the government to direct land reclamation efforts for eventual access as a memorial (Holstein *pers. comm.* 2003). The French government then began the arduous process of clearing the thick vegetative cover, corpses, and unexploded shells from the surface of the battlefield. Next, an effort was undertaken to replant the landscape with trees and manage the forest appropriately as an eventual timber resource. Heavily damaged portions of the battlefield were first replanted with fast growing Scotch pine (*Pinus sylvestris*) seedlings because they were able to tolerate nutrient-poor conditions. The pine forests were eventually thinned and many areas were then replanted to European beech (*Fagus sylvatica*). Today, 88 years after the fighting ended, some areas remain covered with conifers, although the majority of the battlefield is covered with a beech-dominated, deciduous forest (French Forest Service unpublished data).

Physical Setting

The Verdun area receives some of the highest amounts of precipitation (700-800 mm mean annual ppt) in Europe. Precipitation events occur 150-200 days out of the year; 20-50 of these events involve snowfall (Montagne 2003). The average temperatures in January range from 0-2° C in the Meuse River Valley and from 0-5° C in the surrounding uplands. Average July temperatures fall within the 0-5° C range. Figure 13, a climograph from Luxembourg City approximately 100 km to the north, illustrates the general nature of the regions climate.

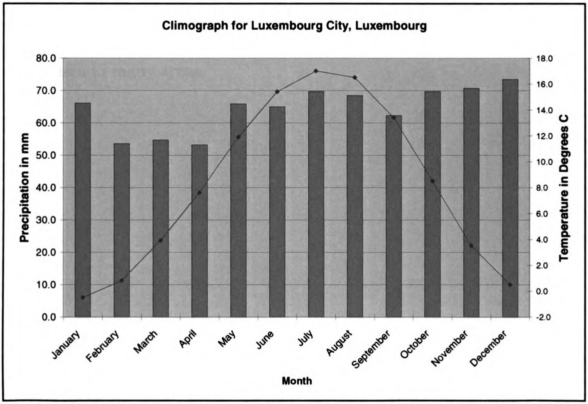

Figure 13: Climograph for Luxembourg City, Luxembourg. The city is located approximately 100 km to the north of Verdun. The line on the chart is for temperature while the bars represent precipitation. *Source: http:www.worldclimate.com*

Pre-war deciduous forests in the Verdun area were dominated by European Beech, 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*) and lesser amounts of Scotch pine (Figure 14). Austrian pines have been planted primarily in areas that are heavily visited, since it is believed the trees cast a memorial like, soft lighting (Figure 15). 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, diverse state. Today, near-monoculture forests dominate the once diverse forest ecosystem in many areas.

Figure 14. Beech tree plantings on Verdun battlefield in May, 2003. Note conifers between beech rows in process of being removed. Source: Author's Collection, May 2003.

Figure 15. Austrian black pine planting near Colonel Driant memorial on the Verdun battlefield. Source: Author's Collection, May 2003.

Bedrock at Verdun consists of gently dipping Jurassic age limestones and shales that comprise the eastern portion of the Paris Structural Basin (Johnson 1921). The dominant geologic/geomorphic feature of the region is the series of northeast-southwest trending cuestas (Figure 16). The cuestas and valleys have been heavily dissected by rivers and streams, thereby providing the region with a great deal (≈200 m) of local relief (Figure 17). Fort Douaumont at 396 meters elevation is situated on the highest point of the battlefield while the eastern portions of the battlefield, on the fringes of the Woevre valley are at elevations of around 200 meters. Erosion-resistant, almost pure, limestone of the late to mid Jurassic Oxfordien (154-146 Ma) formation forms the ridges while a weaker, marly limestone incorporated with thin sequences of shale occupies the valleys (Figure 18).

In the Woerve Valley, east and below the limestone escarpments, lie the erodable shales of the early Jurassic Callovien (160-154 Ma) formation (Johnson 1921). The heavy, clay-dominated soils that formed over the shale and colluvial parent material have slow permeability rates. In addition, these soils are often situated above a water table that is in close proximity to the surface through the majority of the year. Perched water tables are also not uncommon in upland areas and are located where a marl type limestone overlies a silty limestone. Perched water tables occur seasonally, usually from fall until late spring (Ollivier Marcet *pers. comm.* 2003) when snowmelt and spring rains impact frozen soil.

The wet conditions created by the perched water tables impact vegetation and pedogenic processes, especially in cratered areas.

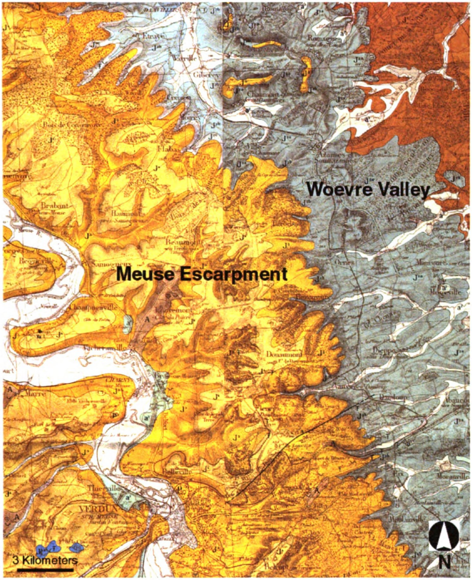

Figure 16. Geologic map of Verdun battlefield and vicinity. The yellow tones represent various grades of limestone making up the cuesta highlands while the blue and dark organge tones comprise the shales of the Woevre valley to the east and northeast. Note the cuesta escarpment along the eastern edge of the yellow highland area. Source: Carte Geologique de la France, Metz and Verdun (1:80,000), 3rd Edition.

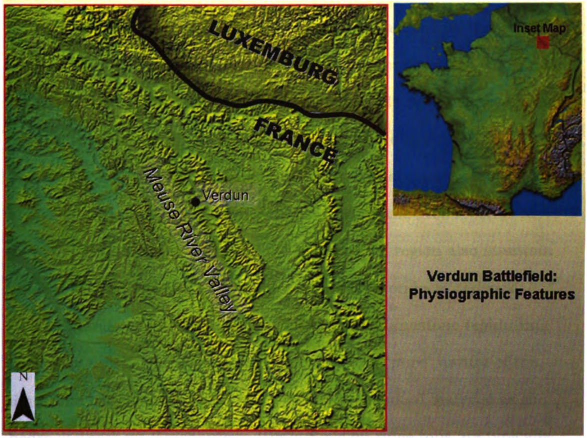

Figure 17. Physiography of the Verdun, France battlefield. The southeast/northwest trending ridges are cuestas, comprised of erosionally resistant limestones of the Paris Basin. Source SRTM digital Elevation data, world wide web.

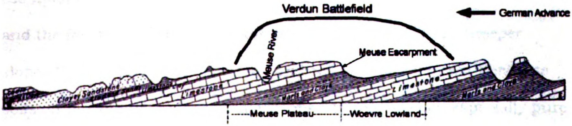

Figure 18. Geologic cross-section of the Paris Basin. Note the steep escarpments facing east - the direction of German advance. This geomorphic character helped slow the German offensive and subsequently contributed towards stalemate conditions along the Western Front. Source: modified from Johnson, 1921

Soil formation in the region is strongly influenced by the generally shallow bedrock, landscape position, and relationship to the water table (Table 1). Most of the soils in the valleys are poorly-drained, according to the NRCS natural drainage classification (Schoeneberger et al. 2002). The area consists of many wetlands and shallow stagnant standing bodies of water during the winter months, when the area receives most of its precipitation. Some of the upland areas in the region also maintain shallow and/or perched water tables, depending on local bedrock.

Upland soils have developed in weathered limestone residuum. Generally these upland soils are thin due to the "pure" nature of the limestone bedrock, which leaves behind little residual material as the bedrock weathers (Duchaufour 1982). Soils on ridge tops are typically more weathered, and therefore thicker, than soils on the slopes (Figure 19). These ridge top soils, in addition to soils on the more gentle slopes of the uplands are mostly Calcic Brown soils (French Soil Classification) and the most common soils within the study area uplands. Steeper slopes that experience more runoff and soil erosion maintain Rendzina soils on the shoulder slopes. An exception to this is when especially pure limestone comprises the ridges, which leads to Rendzina type soils on the ridgetops. Rendzina type soils on ridge crests are often slightly thicker and show more development than Rendzina soils on the slopes. Therefore, the ridgecrests often contain Brunified Rendzinas while the ridge shoulder slopes contain especially thin Rendzina type soils (Table 1).

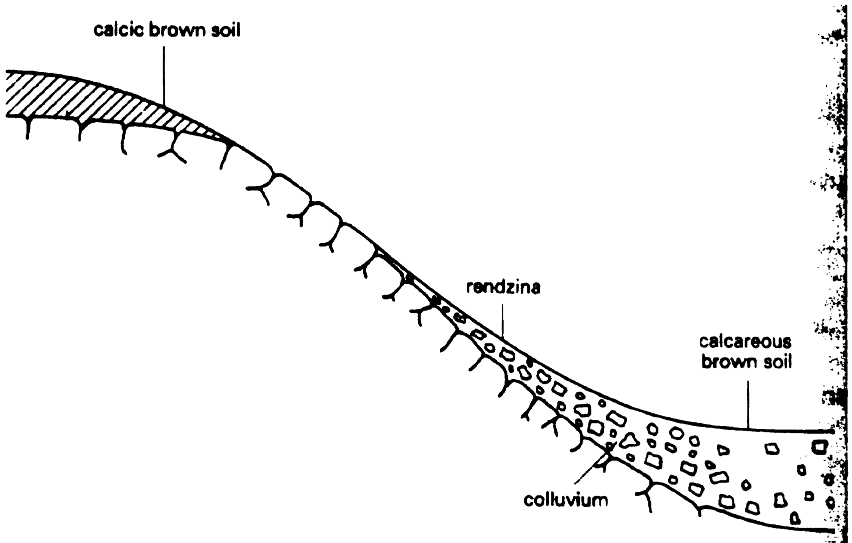

Figure 19. Typical soil catena on Jurassic limestone of northeastern France. Modified from Duchaufour, 1982.

Table 1: Typical soils found on the battlefield of Verdun, France. Source: United States Soil Conservation Service, 1975; Montagne, 2003.

French Soil Classification	**USDA-NRCS Equivalent**	**Parent Material**	**Landscape Position**
Rendzina	Rendolls	"Pure"limestone	Ridge shoulders crests
Brunified Rendzina	Rendolls	"Pure" limestone	Ridge crests
Calcareous Brown Soil	Hapludalfs	Limestone	Ridge back and foot slopes
Calcic Brown Soil	Hapludalfs	Limestone and Colluvium	Ridge Crests
Gley	Hydraquents	Shale and coluvium	Valley bottoms
Pseudogleys	Aquepts	Shale and colluvium	Valley bottoms

Chapter 4
Research Design and Methods

Objective #1: Assessing Landscape Disturbance

Landscape disturbance varies markedly across the Verdun battlefield. In some areas, isolated craters are spaced tens of meters apart, while in other areas the craters are nearly overlapping, divided only by hummocky mounds of blasted-out rubble. Many areas have several smaller craters within preexisting, larger craters. But before any description or assessment of soil development in disturbed areas can be performed, it is important to gain an understanding of the varying magnitudes of disturbance rendered by the battle. Therefore, the purpose of my first objective was to characterize and describe the range of disturbance on the battlefield.

I decided to use soils and geomorphic data as a means of addressing the degree and character of landscape disturbance primarily because the soil surface has largely remained unchanged since the period of initial disturbance (~1916). I decided not to characterize disturbance through the means of bio-ecologic factors, as has been done by others (Flamm and Cravens 1971; Graves 1918; Orians and Pfeiffer 1970; Ridsdale 1919; Westing 1972), for two reasons. First, most of the existing vegetation, with the exception of the lightly disturbed areas, was completely destroyed due to the actions of artillery. Thus, there exists no "control' vegetation sites in many areas, as there is with soils. Secondly, I am examining the battlefield 88 years after disturbance took place. Thus, comparing disturbed vegetation to 'control' vegetation is difficult; trees that predate the war provide the exception rather than the rule in most areas. Vegetation that has replaced pre-war vegetation is mostly either successional growth or replanted forest. Thus, there exists no reliable means by which to gather data to compare vegetation disturbance between the study sites - soils and geomorphic data provide the best means of recording the disturbance magnitude regardless of the time that has elapsed. Therefore, no survey of vegetation was performed to assess disturbance magnitude.

In May of 2003, I first visited the Verdun battlefield to formulate research questions and gain a better understanding of the type and degree of surface disturbances across the battlefield. I realized during this visit that disturbance magnitudes did vary by location. I placed the varying magnitudes of disturbance into several groupings based on amount of pre-war forest still standing, changes to micro and mesotopography, and overall density of craters. Keeping these variables in mind, I determined that the degree of disturbance can be assigned to one of four disturbance categories: light, moderate, heavy, and extreme (Table 2.) This categorization was designed to allow the ranges of disturbance to be easily grouped on an ordinal, qualitative scale without being too general, and yet not with so many categories that it created confusion (such as may occur when an inordinately large amount of categories are assigned or designated.). The classification scheme is designed so that an individual familiar with the ranges of disturbance on the battlefield can quickly categorize an area's disturbance based on a quick examination of the forest cover and surface topography. The classification was also designed to be applicable to other areas disturbed by explosive munitions without creating the need to expand or generalize the four categories. An individual can enter a disturbed area, make a quick assessment of the surface and forest cover, and then decide on the disturbance based on the extremes of Table 2.

Table 2: Categories of disturbance magnitude among the five study sites at the Verdun battlefield

Disturbance magnitude Category	**Crater density**	**Magnitude and type of forest disturbance**	**Magnitude and type of soil disturbance**	**Microtopography characteristics**
Light	Sparsely spaced individual craters	Many pre-war trees still exist; some damaged by shrapnel	Many areas of undisturbed soils remain; disturbance limited to area within and adjacent to craters	Generally level surface, broken by the occasional crater
Moderate	Abundant craters spaced generally evenly; some closely spaced clusters	Most pre-war forest destroyed; some pockets of undisturbed forest exist	Majority of soils disturbed; some areas of undisturbed soils remain	Surface mostly dented by craters; surface is level between craters
Heavy	Craters dominate surface, many overlap	Original, pre-war forest completely destroyed; dead tree trunks can be found	Surface nearly completely disturbed	Level areas between craters are rare to nonexistent
Extreme	Craters inundate surface; smaller craters common within larger craters	Pre-war forest completely destroyed	Soil disturbance complete to depths exceeding eight meters	No remnants of original surface remain

For example, if the area contains some areas of undisturbed soils, but very little original forest, the individual would determine that it is neither lightly nor extremely disturbed. Further scrutiny will allow the individual to determine if the disturbance is heavy or moderate, without the burden of over-categorization. Prior works have categorized disturbance from war, but were conducted shortly after the disturbance (war) occurred and were based primarily on lumber value, and did not include geomorphic criteria (Pfeiffer 1969; Ridsdale 1916; Westing 1976). My categorization is unique in that it includes geomorphic criteria in its formulation.

Using/applying these disturbance categories, I identified five representative sites for detailed study upon a return visit to the battlefield in September, 2004 (Figure 20). These sites were selected to reflect the spectrum of disturbance across the Verdun battlefield. For example, the Etraye site was selected because the disturbance was notably light while the site at Thiaumont Platform was chosen because the disturbance was clearly extreme. The other sites were selected to represent disturbance degrees between these two extremes. Other site selection criteria included the need for similar bedrock, soils, and topography, allowing only the degree of disturbance to vary among them. Each study site is approximately 0.5 hectares in area, contains primarily calcareous soils over limestone bedrock, and is situated on the summit and shoulder slopes of gently to moderately sloping, upland surfaces on erosionally resistant ridges (Figure 21).

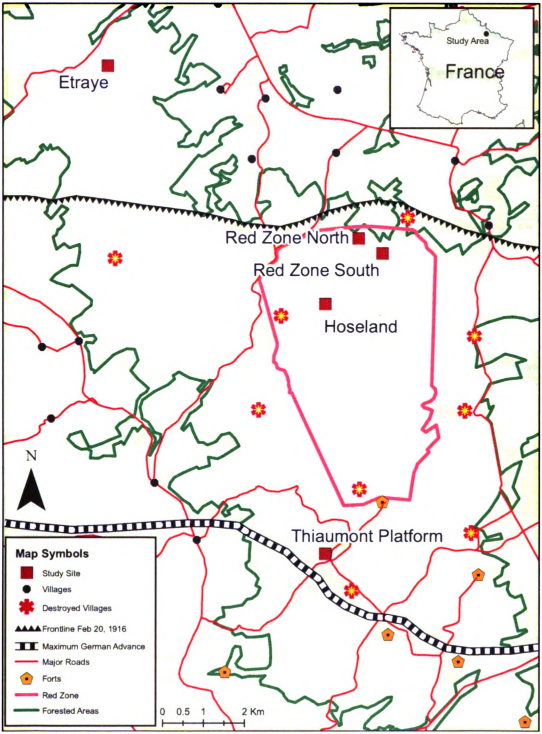

Figure 20. Surface disturbance plots that were studied on Verdun, France battlefield.

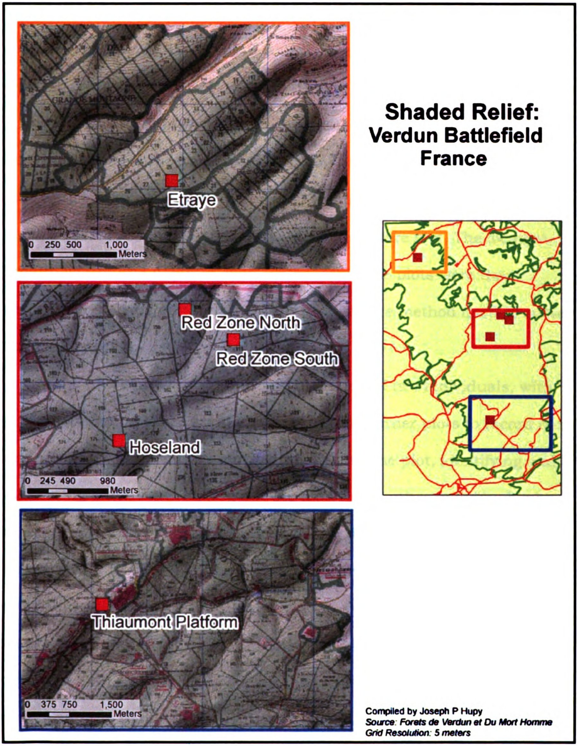

Figure 21. Local relief of surface disturbance study sites on Verdun battlefield. The outline of each relief map is shown in matching color and order on the inset map.

At each site, two 50x50 meter, representative plots were surveyed and marked using a GPS unit, a sonic range finder, and an azimuth bearing compass. The GPS unit was used to record, in UTM coordinates, a known starting point from which the remainder of the plot would be surveyed. From this recorded starting point the remaining corners of the plot were surveyed by placing stakes 50 meters from the starting point at right angles, thus making a square, quarter-hectare plot. The location, length, width, and depth of each crater within the plots were then recorded by relying on the same azimuth-distance method used to survey the plot boundaries.

The procedure required the participation of two individuals, with one person remaining stationary on one of the corner plots to record data and the other methodically moving throughout the plot, identifying and measuring craters and calling out the data to the other individual, who recorded the data in a field notebook. Using a known starting point, in this case the plot corners, the stationary individual would stand at this point and obtain the distance and azimuth direction to a given crater within the plot. The individual in charge of finding the craters was equipped with a targeting device for the sonic range finder and a measuring rod to obtain crater dimensions. After a crater was identified[12], the distance, azimuth, length, width, and depth of the crater were recorded and the crater was then marked with a pin flag to prevent

[12] Any surface indentation that had a round to oblique shape was considered a crater minimum size. No minimum or maximum size limit defined a crater.

re-counting. This procedure was repeated until all craters within the plot were counted and recorded. These raw data were later compiled and entered into ARCGIS™ software using the survey analyst extension. This extension allowed for import of the data in database format into a GIS, facilitating the plotting of the location of each crater within the quarter hectare plot based on its azimuth and distance from the UTM coordinates of the plot corners. The extension also allowed me to import the data about the dimensions of each crater, so that each crater could be described quantatively, based on its area. I was able to make interpretations concerning disturbance magnitude of the soil landscape, variability of crater size, density, and the percentage of the ground surface covered by craters, using these spatial data.

Survey of Changes in Microtopography Due to Cratering

The battle at Verdun dramatically changed the microtopography of the landscape. Whereas the survey of craters within the 50x50 meter plots (described above) is useful in quantifying the size and density of the craters on each study site, it does not provide continuous spatial information about meso and microtopography. Thus, a topographic survey at each of the five study sites was performed to provide a second means of assessing landscape disturbance magnitude. The topography of each plot at the five study sites was surveyed by running three, 50-meter transects, at 15-meter spacings, across the plot, in a direction perpendicular to the contour. Elevations at 0.5 meter increments along the transect were recorded to the nearest centimeter using a sonic distance range finder, a survey stadia rod and a hand leveling device (Figure 22). The data were then plotted as a line graph without vertical exaggeration to create a topographic profile. The profile generated from this survey was also used to quantify the amount of material displaced along the transect lines, which is another means of assessing site disturbance. This information, when presented in graphical format, readily allows for visual comparison of disturbance magnitude, which contrasts nicely with the quantitative data obtained from the crater survey plots.

Data from both survey methods were used to quantify the extent of and variability of soil and surficial disturbance across the battlefield. No previous study has attempted to quantify the extent of soil or landscape disturbance due to explosive munitions. Previous research has, instead, focused on the immediate effects of warfare by mainly quantifying *vegetative* disturbance (Pfeiffer 1969; Ridsdale 1916; Westing 1976).

Figure 22. Survey of microtopography. Individual on left is holding a leveling device while individual in the crater is holding a stadia rod in an artillery crater. Measurements were taken every 0.5m along 50-meter transect.

Gaining an understanding of the effects of warfare on the physical landscape is important. Equally important, however, are data that address the long-term *ramifications* of warfare, or the ability of a particular landscape to recover. Landscape recovery, in the form of soil development, is addressed in my second research objective. Keep in mind however, that the term 'recover' is loosely applied here since, based on the disturbance data gathered in objective one, the landscape has never truly reverted back to its original state. The landscape has changed and remains changed, however the original destruction has largely been erased due the landscapes ability to 'recover' from such a disturbance. Therefore, when the term recovery is used, it is meant more so as 'healing' the original surface disturbance in the form of vegetative succession and soil development.

Objective #2: Assessing Post-War Landscape Recovery

Historical accounts and contemporary descriptions have documented the intense and widespread disturbance on the Verdun battlefield (Clermont-Ferrard 1919; Horne 1993; Martin 2001; Ousby 2002). However, beyond descriptions of how the landscape appeared immediately following the battle and a brief mention of the contemporary landscape, the degree of landscape recovery at Verdun has not been discussed in the scientific literature. Landscape *recovery* from these types of disturbances is of interest because not only does it contribute to the growing body of literature concerning human impact on the physical environment, but it also adds insight into how landscapes subsequently evolve following catastrophic disturbances. Questions that can be used to describe landscape evolution following disturbance from explosive munitions include the following:

- To what extent has the landscape been disturbed?
- To what extent has the landscape been changed and how has its progress towards recovery progressed?

- How has this landscape evolved along different process pathways following disturbance?

In chapter one, the ability of a landscape to resist and/or recover from various forms of disturbance was defined as landscape *resilience* (Miles et al. 2001). Often, landscape resilience is determined by various bio-ecologic measurements (Miles et al. 2001; Usher 2001; Wali 1999). The drawback to relying solely on bio-ecologic measures is that the whole of the landscape is not taken into account. That is, most of these parameters ignore surface instability and degradation, as well as soils and soil development - parameters which also reflect overall landscape resilience. Geomorphologists have therefore expanded upon the concept of landscape resilience by including geomorphic factors into what they call *sensitivity*; i.e. the stability vs instability of a landscape (Brunsden and Thornes 1979). For example, a stable landscape contains surfaces that do not easily erode and that recover quickly from disturbances that would otherwise induce erosion/burial. Under such stable conditions, soil formation can proceed relatively uninterruptedly. Basically, the more developed a soil is, the longer it has been around and thus, soils are often used as indicators of stable surface or slope conditions (Birkeland 1999). Most soil-related applications, however, have been a part of long-term landscape studies, such as research involving Quaternary environments (Balek 2002; Dan and Yaalon 1968; Parsons, Balster, and

Ness 1970), because soils generally take a long time to develop and therefore reflect long periods of landscape stability (Birkeland 1999; Gile, Hawley, and Grossman 1981). However, because soils develop slowly, they have largely been ignored in *short-term* landscape recovery studies (Thomas 2001). Indeed, only a limited amount of research has examined soil properties as an indicator of short-term recovery under both natural and human forms of disturbance (Beyer et al. 2001; Grieve 2000, 2001; Mueser and Blume 2001; Roberts et al. 1988; Schleuss, Wu, and Blume 1998). And studies that *have* examined soil development after disturbances usually focus on disturbance by commercial non-warfare activities, e.g., mining or logging operations (Lebedeva and Tonkonogov 1995; McPherson and Timmer 2002; Roberts et al. 1988; Wali 1999).

Regarding disturbance from military/wartime activities, several studies have examined the ability of a soil surface to recover after being subjected to tank traffic (El and Al 1996; El-Baz et al. 1993; Gatto, Halvorson, and McCool 2001; Nichols and Bierman 2001; Prose and Metzger 1985). Taken together, this limited body of research suggests that research on soils as indicators of landscape recovery following anthropogenic disturbance is needed. An even larger dearth of research exists when soil parameters are used to examine landscapes affected by the actions of war. My goal in this research objective is to apply the principals of soil geomorphology to landscapes affected by war.

Soil Development Theory

A variety of theoretical models have been used to describe soil development as influenced by a combination of outside factors or through a series of internal processes (Jenny 1941; Johnson and Watson-Stegner 1987; Runge 1973; Simonson 1959). Among these models the best known, and most referenced, is the Jenny (Jenny 1941) state-factor model, in which soil formation is assumedly based on the influence of five soil-forming factors: climate, organisms, relief, parent material, and time. The model serves as a simple way of stating that soil formation is a function of one or a combination of the above factors. However, the model has its drawbacks, since it is mostly qualitative and the factors are somewhat overlapping (Huggett 1976). Thus, it is difficult to obtain data to determine how much faster one soil is developing compared to another. Basically, the model does nothing to explain how a soil system acquires its properties, via pedogenic processes; it merely states the factors that lead to the development of a particular soil and highlights their interaction (Amundson and Jenny 1997). While the model serves as an excellent tool for teaching purposes, the soil forming factors are fairly conceptual. Thus it is difficult to quantify soil development rates unless the soil-forming factor can be isolated and compared between several soils that are influenced under varying degrees by the given factor.

Simonson (1959) attempted to elaborate on the drawbacks of the Jenny model by explaining soil formation as influenced by a series of processes that include additions, removals, transfers, and transformations. However, his model fails to elaborate on the specific processes involved in soil formation.

Johnson and Watson-Stegner (Johnson et al. 1987) combined both soil-forming processes and factors to propose that soil formation is always in a dynamic state, undergoing both progressive and regressive states of development. The model is useful in explaining soil evolution, but too general to apply towards specific rates of soil development between undisturbed soils and soils in artillery craters.

For my study, I applied a pedogenic model that is more focused on specific processes of soil formation. The other models described above fit certain components of my research, but do not focus on key processes occurring on crater bottoms such as organic matter accumulation and infiltration/percolation. Therefore, I determined that the best model to apply to my research is that of Runge (1973), *aka* the Energy Model, because it allows me to isolate and examine specific processes of soil formation whose products should be measurable at Verdun even after only 87 years. The Runge Energy Model

$$\mathbf{S=f\,(o,\ w,\ t)},$$

assumes that soil development (S) is primarily a function of organic matter (OM) production (o), the amount of water available for leaching (w), and time (t). Infiltrating water is assumed to be the primary energy vector driving soil development. Most would agree that soil development is enhanced as more water moves vertically through the soil column; the energy model builds this assumption directly into its formulation. Conversely, when water is lost on the surface due to runoff or when water movement is retarded due to a high water table, soil development is not enhanced; it may even be impeded.

In the Energy Model, OM production is viewed as a renewing vector, and an impediment to soil development. The model was developed amidst the grassland soils (Mollisols) of Illinois, where organic matter coatings protect soil particles from weathering, and at the same time, the biocycling of bases by plants keeps pH levels high, and in so doing inhibits translocation of clay and the formation of Bt horizons. Runge also noted OM accumulation when there was a lack of mineralization of OM due to a high water table that retarded the decomposition of OM in the soil column. Basically, the high water table resulted in (1) a loss of the energy of water moving through the profile and, (2) absences of aerobic microbes that were able to mineralize the organic contributions to the soil. Based on these observations, Runge listed the presence (or abundance) of OM as a limiting factor in soil development. Although the Energy Model works well in grassland soils, Schaetzl (1990) found that, in forest soils, OM production enhanced, rather than retarded soil development due to the production of organic acids that promoted litter decay and weathering within the soil column. He noted that treethrow pits were loci of increased infiltration and areas where OM preferentially accumulated – both acted in unison to accelerate soil development in pit sites.

In the forested soils of Verdun, the model predicts that soils within artillery craters will exhibit enhanced development because they are within an area of greater leaching (more "*w*"). However, where perched water tables exist, soil development may actually be retarded due to lack of percolation, even within craters. Applying the principles of the Runge model, under perched conditions the energy of water movement through the soil profile is lost and soil development will be impeded.

The data from this dissertation, therefore, have the potential to serve as a verification (and application) of the "w" part of the Runge model, by showing that, in forested environments; soil development is largely driven by the energy of water movement through the profile. Based on Schaetzl's (1990) work and principles of the Runge model, the depressions (craters) should serve as areas of increased water moving through the profile. Like Schaetzl's (1990) work, these depressions are also, however, a collection point for large amounts of litter. Increased amounts of water movement through the profile serve to break down the litter into humified organic matter, which forms organic acids that may contribute to enhanced weathering. Therefore, another possible outcome of this work is to not only to verify the Runge model, but to provide a caveat to the Runge model that accumulations of O.M. within the soils column are not necessarily a sign of retarded soil development, as did Schaetzl (1990).

Translocation of cations, and OM accumulation are some of the first measurable pedogenic properties in young soils (Schaetzl, Barrett, and Winkler 1994; Beyer et al. 2001; Roberts et al. 1988). Based on the above discussion, I applied the principles of the Runge Energy Model to my data as a guide for my interpretations of soil development/recovery at the five research sites. As an indicator of the effectiveness of the *w* factor, I examined the degree of leaching and translocation of various cations inthe soil profile. Generally, leaching refers to materials that are taken out of the soil and translocation refers to downward movement of those materials within the soil column. By comparing the degree of leaching and translocation of various cations within craters, I can determine weathering rates of newly exposed parent material

To indicate the effectiveness of the *o* factor, I examined the texture of the upper horizons, and the amount of organic matter that has accumulated in, the O and A horizons. My sampling and data acquisition design (below) reflect the approach I used to gather data that fit within these two pedogenic vectors.

Sampling Design

Data from disturbed soils within craters were compared to that from undisturbed soils in order to address my second research objective. The focus of this discussion is on organic matter accumulation, degree of translocation of soluble cations vs those that are found mainly in stable and insoluble materials, translocation of clay, and water table relationships; these are soil development principles whose explanation is treatable within the conceptual context of the Runge (1973) model.

To compare soil development in disturbed and undisturbed areas, I excavated and sampled undisturbed soils next to craters, as well as disturbed soils within craters. I chose sites that had a limited amount of disturbance with large areas of undisturbed soils adjacent to craters. I also based and stratified my selection criteria on soil properties. The soils the Etraye site are Brunified Rendzinas over nearly 'pure' limestone bedrock (Table 3). The Red Zone soils are Calcareous Brown soils, which have developed on a more weathered but less 'pure' limestone (Table 4). Soils at Bois de Thill are Pseudogleys over nearly pure, clayey colluvium valley deposits (Table 5). Two of the study sites (Etraye and Red Zone) are in the vicinity of the disturbance study plots while Bois de Thill is in a new location. The new location was chosen to represent soils that are in a poorly drained, high clay content soil with a parent material other than limestone. The site was also selected to represent soils other than those on the upland ridges of the Meuse heights.

To view, describe and sample the soils, trenches were excavated across three craters representing the typical range of crater sizes at each of the three soil development study sites (Figure 23). Trenches were excavated with a backhoe to a depth of one meter or until reaching limiting impediments such as bedrock or a high water table. The backhoe trenches extended across the entire width of each crater, onto the undisturbed soils adjacent to that crater (Figure 24). Data from undisturbed soils adjacent to the craters were used as a baseline to which the data from the disturbed sites were compared.

Table 3: Typical pedon description[a] of a Brunified Rendzina soil at the Etraye site

Horizon	Depth (cm)	Color[b] (moist)	Structure[c]	Consistence[d] (moist)	Bdy[e]	Coarse Frags[f] (estimated, by volume)
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

a: Descriptions based upon Soil Survey Division Staff (2002)
b: Hue, Value, and Chroma according to Munsell Soil Color chart
c: Abbreviations: m: medium, c: coarse, gr: granular, sbk: sub-angular blocky
d: Abbreviations: VFI: very firm, FI: firm
e: Abbreviations: CI: clear irregular, gradual irregular, gradual wavy, gradual wavy
f: Abbreviations: coarse gravel (20-76 mm)

Table 4: Typical pedon description[a] of a Calcareous Brown soil at the Red Zone site

Horizon	Depth (cm)	Color[b] (moist)	Structure[c]	Consistence[d] (moist)	Bdy[e]	Coarse Frags[f] (estimated, by volume)
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

a: Descriptions based upon Soil Survey Division Staff (2002)
b: Hue, Value, and Chroma according to Munsell Soil Color chart
c: Abbreviations: m: medium, f: fine, vf: very fine, gr: granular, sbk: sub-angular blocky, abk: angular blocky
d: Abbreviations: VFI: very firm, FR: friable, VFR: very friable, L: loose
e: Abbreviations: AS: abrubt smooth, CS: clear smooth, CW: clear wavy, GW: gradual wavy
f: Abbreviations: MG: medium gravel (5-20 mm), CB: cobbles (76-250mm) CG: coarse gravel (20-76 mm)

Table 5: Typical pedon description[a] of a Psuedogley soil at the Bois de Thill site

Horizon	Depth (cm)	Color[b] (moist)	Structure[c]	Consistence[d] (moist)	Bdy[e]	Coarse Frags[f] (estimated, by volume)
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 med gravel

a: Descriptions based upon Soil Survey Division Staff (2002)
b: Hue, Value, and Chroma according to Munsell Soil Color chart
c: Abbreviations: f: fine, m: medium, c: coarse, gr: granular, sbk: sub-angular blocky
d: Abbreviations: FI: firm, VFI: very firm
e: Abbreviations: CS: clear smooth, GW: gradual wavy
f: Abbreviations: MG: medium gravel (5-20 mm)

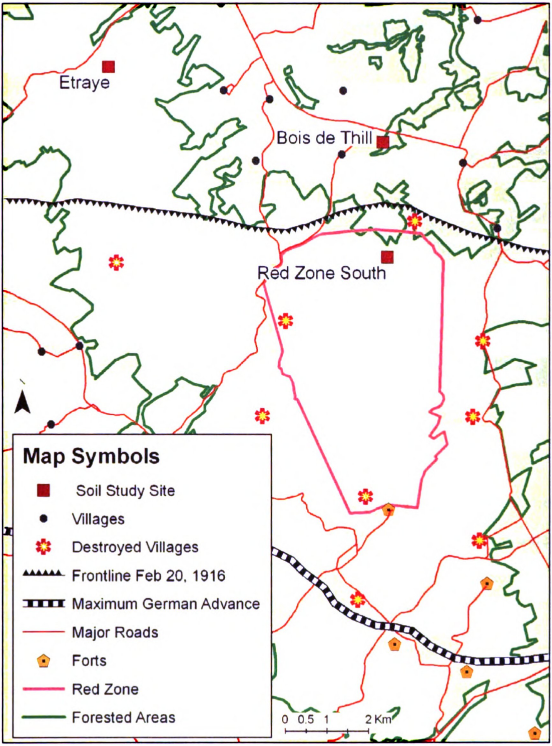

Figure 23. Distribution of soil development study sites across the study area of Verdun, France.

Figure 24. Backhoe excavating a trench across a typical crater on the Verdun battlefield of France. Line outlines profile of the crater.

Soil profiles were then described and sampled from the face of the backhoe trench according to NRCS guidelines (Staff 1993). Descriptions and samples were taken from three pedons in the following positions within the trench: crater bottom, crater side, and in the undisturbed soils adjacent to the crater (Figure 25). Samples of approximately 500 grams were then removed from the profile face at depths of 10, 20, 30, and 50 cm, air-dried in France, and transported back to the USA in sealed, plastic sample bags. Coarse fragments were removed from the samples in the MSU Geography soils' lab by gently crushing and then repeatedly passing the soil through a 2mm sieve.

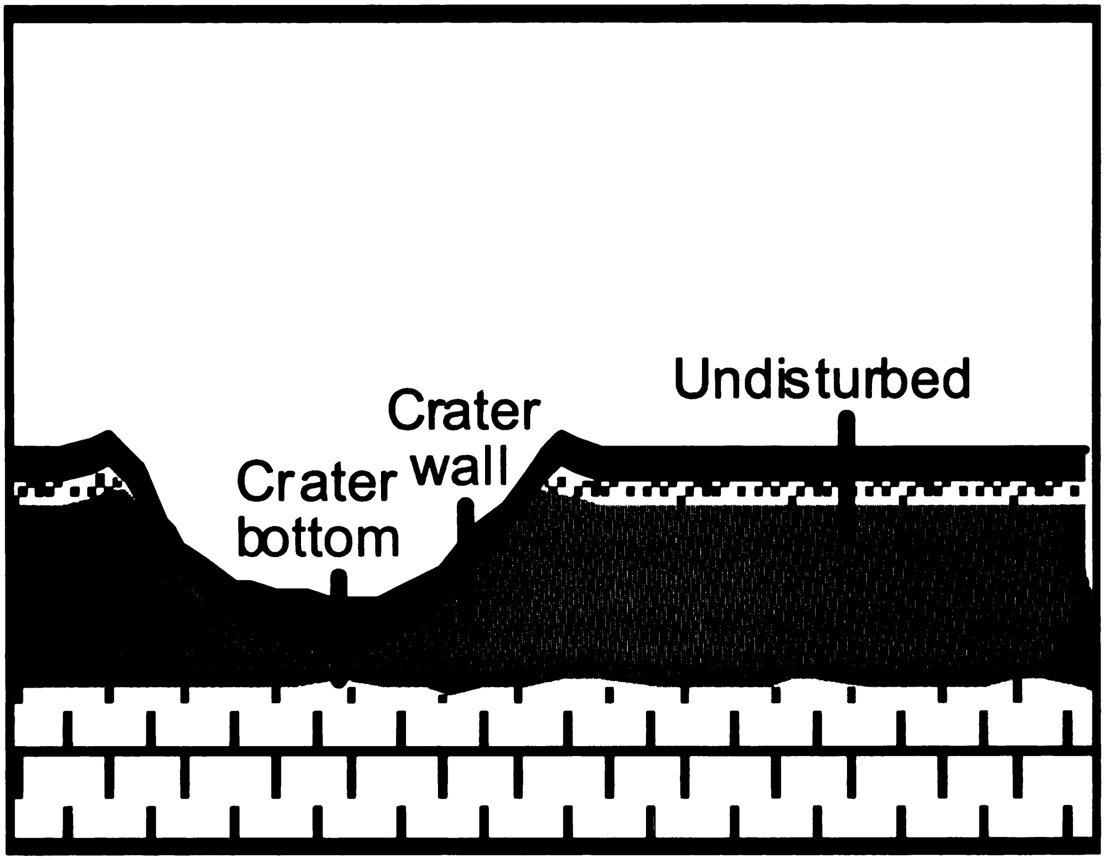

Figure 25. Typical artillery crater and location of sampled pedons. Each pedon was sampled at depths of 10, 20, 30, and 50 cm below soil surface.

Degree of soil development is often associated with the differential translocation of soluble vs insoluble constituents (Singh, Parkash, and Singhvi 1988). Particularly useful in this regard are the amounts of weatherable and translocatable minerals vs those that are not (Howard, Amos, and Daniels 1993). Certain minerals such as tourmaline and zircon are highly resistant to weathering and will remain in the soil profile while other less resistant minerals like olivine, plagioclase feldspars, and biotite will be preferentially removed via weathering processes. However, some of these minerals such as zircon and tourmaline are rare in soils while other minerals are not easily identifiable. Elemental data are often used as a surrogate for mineralogical data (Busacca and Singer 1989; Murad 1978; Santos, St. Arnaud, and Anderson 1986) because certain elements only derive from their parent minerals. For example zirconium mainly derives from the resistant mineral zircon, and titanium derives mainly from the minerals rutile, tourmaline, and anatase. Thus, by comparing certain 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 mineralogy, and hence, weathering (Murad 1978).

In this study, the degree of translocation of soluble materials was examined by comparing the ratios of elements from easily weathered minerals, e.g., Ca, Na, K, to elements from minerals that are more resistant to weathering and translocation (Fe, Zr, Ti), by depth (Beavers et al. 1963; Evans and Adams 1975; Howard, Amos, and Daniels 1993). Such data can be used not only to evaluate the uniformity of the "control" soils, such as the undisturbed soils adjacent to the craters, but also to compare pedogenic development among horizons and study sites.

To prepare the samples for elemental analysis, I first ground each to silt size (approx. 30-50 micrometers in mean diameter). Three grams of this finely ground powder were then diluted by adding 9.0g of lithium tetraborate ($LI_2B_4O_7$) and 0.5g of ammonium nitrate (NH_4NO_3) as an oxidizer. This mixture was then melted in a platinum crucible at 1000°C of oxidizing flame for >20 minutes while being stirred on an orbital mixing stage. The melt was poured into platinum molds to make glass disks, which were analyzed with an X-ray fluorescent (XRF) spectrometer within the Geosciences Department at Michigan State University. 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. Software for reduction was supplied from Bruker's Spectraplus software.

From these reduced data, a number of possible ratios were examined that might best illustrate the degree of translocation of relatively mobile vs immobile elements, and hence weathering and soil development. I chose the ratio of (Zr+Ti)/(Ca+Mg+K) to assess weathering in the profile, because it compares immobile elements (considered to reflect minerals in the soil that are stable and in an unweathered state) to common elements that represent minerals in the parent material that are easily weathered and highly mobile. For example, the limestone parent material ($CaCO_3$) will have retained the minerals containing Zr and Ti while the more easily weathered Ca, Mg, and K will have been weathered out of their parent minerals and, presumably, rendered translocable (Busacca and Singer 1989). Other ratios were also attempted that placed larger numbers of mobile elements in the denominator, but the results were similar and I choose to use this simpler ratio that contained elements commonly found in soils formed in limestone residuum.

Other indicators of soil development include pH, texture, and organic matter content. Analytical procedures to obtain data on these indicators were performed in the Geography department's soil geomorphology laboratory at Michigan State University. In soils formed in calcareous parent materials and developing under leaching environments, pH generally increases with depth. Such is the case at Verdun, where residual soils have formed on calcareous bedrock (Duchaufour 1982; Montagne 2003). Conversely, underdeveloped or thoroughly mixed soils should contain uniform or erratic pH values throughout the profile. Soil pH values were determined in a 2:1 water:soil suspension using a handheld electronic pH meter (Model IQ150, Scientific Instruments Inc.). To maintain consistency and to ensure accurate pH levels, the 2:1 suspension was stirred after one hour with a glass rod, and then after another hour had passed the probe was inserted into the suspension to record the pH.

Particle size analysis can be used to illustrate clay translocation (lessivage) (Creemens and Mokma 1986; Dixit 1978). Increased amounts of clay in the lower profile are commonly taken as signs of clay translocation, which has assumedly been driven by percolating water - hence its application to the Runge model. Soil textural analyses were conducted via the pipette method (Day 1965) on all samples except those containing mainly organic material, i.e., O horizons. Sand sized particles were removed by passing a pre-weighed, dispersed, oven dried soil sample, weighing 10-12 grams, through a 53 micrometer sieve directly over a 1000 ml cylinder. Then, the sand sized particles (2.0 – 0.05 mm) remaining in the sieve were dried at 104 C. The dried sand fraction was then weighed again to the nearest 0.01 gram and further dry sieved to obtain sand fraction data as well. The silt and clay sized particles that washed through the sieve were pipetted after a specified amount of time (~8 hours) based on settling rates of the particles at a given room temperature, using Stokes' Law.

The accumulation of organic matter in the soil profile serves as one of the first indicators of soil development in recovering disturbed soils (Beyer et al. 2001; Roberts et al. 1988). Typically, recovering disturbed soils will develop an O horizon before any other. This will be followed by the development of an A horizon as the organic material is broken down and incorporated into the soil profile (Birkeland 1999; Schaetzl and Anderson, 2005). I used the loss on ignition (LOI) procedure to determine organic matter content of my soil samples (Davies 1974). Samples (~25 g) were first oven dried overnight at 104 C and then weighed to the nearest .001 g before being placed into an oven for 8 hours at 340 C. After this, the sample was cooled in a dessicator and weighed again. The LOI procedure is used to determine the amount of organic carbon in the sample by 'cooking off' the organic matter as CO_2. To obtain the percentage of organic carbon (OC), the following two equations are used (Davies 1974):

LOI = (oven dry soil wt. – soil wt. after combustion) / (oven dry soil wt.) X 100

OC (%) = LOI/1.72

Taken together, these analytical procedures facilitate observations on the degree of soil development in craters compared to undisturbed areas. In the remaining chapters of this dissertation I will report and discuss the results of the data I gathered using these procedures and methods.

Chapter 5

Results and Discussion

Objective One

Disturbance Influences

The purpose of my first research objective was to characterize and describe the range and character of disturbance on the Verdun battlefield. During a preliminary trip to the battlefield in May of 2003, and before I even began to set up my experimental design, it became apparent that the degree and intensity of disturbance varied markedly across the battlefield. My data and field observations show that the differences in disturbance magnitude are mainly a function of various combinations of four separate variables, which vary spatially (and somewhat predictably) across the battlefield:

(1) Location of armies in relation to the front lines;

(2) Degree of stagnation of front lines;

(3) Position of armies in relation to topographic position on the landscape; and

(4) The characteristics of the underlying parent material or bedrock.

Each of these variables will be discussed in detail below, followed by a discussion of disturbance magnitude at each of the five study sites.

Of the four variables listed above, the location(s) of the front lines exerted the most influence on landscape disturbance. Fighting in WWI was based upon massive concentrations of firepower from fixed positions of entrenched artillery (Mosier 2001), and Verdun typified this usage of artillery (Horne 1993). The front line trenches were filled with infantry and were thus subsequently prime artillery targets for both German and French gunners. Each side was attempting to make forward gains of sometimes just several hundred yards to seize trenches and territory of the opposing army, but the offensive capabilities of the time were outweighed by the defensive capabilities of the infantry machine guns and bunkers along a line of fortified positions. This meant that destruction to the landscape and the enemy was mainly limited to the objectives and range of the artillery.

Although the disturbances on the Verdun battlefield are often of a higher magnitude than that of other areas along the western front in Europe, the same pattern of destruction can be witnessed along the entire length of the front from the English Channel to the Swiss border. The disturbance is greatest in the immediate vicinity of the front line, often referred to as 'no man's land'. Moving away from no man's land, the degree of destruction/disturbance generally diminishes. On the Verdun battlefield, as elsewhere along the western front, beyond the 20 km range of the heavy artillery, the countryside is virtually untouched by the spoilage of war. In these outlying areas, there are often only sporadic large craters associated with some of the heavier siege guns of the war.

Stagnation of the front lines is closely related to the first variable - proximity of armies to the front lines. Because WWI was often associated with stalemated fighting conditions, the first two variables (stagnation and location of trenches) frequently coincide. In some cases however, fighting along the Western Front and, for that matter, Verdun, witnessed fluid movement of armies. In the case of Verdun, these conditions occurred at the beginning of the battle when the Germans made massive gains due to the surprise nature of the offensive, and at the end of the battle when the German army was so demoralized it had no will to fight and was making an orderly retreat back to an already fortified defensive position at the Hindenburg line (Mosier 2001). Destruction/disturbance associated with artillery accompanied these fluid conditions but the damage was less extensive and limited to smaller, more mobile artillery pieces. In addition, because the armies were not in one place for more than a few days at most, the degree of shelling that the forests and soilscape received was light compared to when stalemate conditions left armies fighting over a 500 yard swath of land for months.

Because of stalemate conditions and the long, accurate range of infantry weapons, most artillery in WWI was situated well beyond (behind) the front lines. Prior to WWI, artillery gunners were on much smaller fields of battle and used iron sights to fire directly into oncoming troops. This type of artillery was situated in the immediate vicinity of the 'action' and the intent of the artillery was mainly to cut up massed enemy formations (Gudmundsson 1993). In WWI, however, commanders and officers quickly realized that the long, accurate, rapid-fire nature of infantry weapons was rendering the capabilities of current artillery tactics virtually useless. Artillery was therefore pulled further and further back from the front lines. The previously unrefined concept of indirectly firing at an unseen enemy using trigonometric equations became the norm. Therefore, gunners were firing at targets established by foreword observers and aerial observation platforms, such as planes and blimps. In this type of indirect artillery firing tactics, hitting a target on the *backside* of a ridge proved much more difficult than hitting the crest or fore-slope.

Armies were quick to note that they were easy targets when on a ridge crest because this is what the gunners used to sight in their artillery pieces. Before long, both sides realized that the crests and facing hillslopes on high-ground were most vulnerable to artillery fire and the slopes facing away, or back slopes, were least vulnerable. Unfortunately for those infantry groups on the front, the fore slopes and ridge crests still had to be occupied in order to observe the enemy and stave off on surprise offensive movements. These positions were favorite targets of the artillery and, as much of artillery gunners tried to place their sights on the back-slopes, ridge-crests and foreword slopes received the brunt of artillery barrages. This led to slopes and hillcrests facing the enemy incurring much more damages than the back slopes. Thus, the location of armies in relation to topographic position is a variable that influenced the degree of disturbance across the battlefield.

Crater width and depth varied according to the nature of the geologic parent material, i.e. bedrock and sediment. During the course of performing my field work, I observed that in areas with deeply weathered bedrock and thick soil profiles, craters were generally deeper and steeper sided than areas of shallow, lithic soils. When the nature of the parent material was colluvium over shale, the craters were often deeper and wider than were craters over shallow, dense limestone bedrock. In areas with perched water tables, the craters were much wider than they were deep, probably due to eventual collapse of wet soil along the sides of the crater. The craters may have originally have been of the same size as at other site, but with the mass wastage of material on the crater sides over time, they have become much shallower in these areas.

Of course, when larger artillery rounds are considered, regardless of underlying geologic conditions, the craters take on a similar nature because the blast is so powerful that it will exhume roughly the same amount of material regardless of bedrock type. For example, a 420 mm 'Big Bertha' round will produce the same size crater over pure limestone bedrock that supports Rendzina soils as it would in unconsolidated colluvial sediments within the Woevre valley. In addition, in those areas that were under repeated heavy shelling, the underlying geology becomes less and less significant because the disturbance to bedrock was everywhere extensive, pulverizing the uppermost bedrock and, forming a heterogeneous mass of rock fragments and heavy, clay-rich sediments. Crater size and depth in these conditions were limited only to the viscosity of the sediment and the size of the artillery round.

In conclusion, while the first three variables of disturbance influenced the degree of disturbance across the battlefield, the last variable, bedrock (depth to and type), did not influence the degree of disturbance so much as it influenced the nature of the each individual cratered disturbance.

Disturbance Characteristics of Study Sites

Generally, based on my observations and from my limited sample of five study plots, disturbance increased in magnitude moving from north to south within the study area, closer to the center of the fighting (Figure 12; Tables 6, 7, 8). Variation in the amount of disturbance, from north to south at Verdun, can be attributed to other disturbance magnitude variables such as topographic location and stagnation of the front lines, or combinations of the two. Site disturbance magnitude will be discussed below for each of the five study sites by starting with the northern most site, Etraye, and concluding with the southern-most, Thiaumont Platform.

Table 6: Disturbance attributes based on data from ¼ hectare plots at five study sites on the Verdun battlefield.

Site Name	Craters in Plot (n)	Craters / km^2	Total Area of Plot Disturbed (m^2)	Plot Disturbance (% of area)
Etraye 1	70	2800	593.6	23.8
Etraye 2	49	1960	420.8	16.8
*Site Mean, S.D.**	*59.6, 14.8*	*2380.0, 594.0*	*507.2, 122.2*	*20.3, 5.0*
Red Zone North 1	87	3480	552.0	22.1
Red Zone North 2	115	4600	706.1	28.2
Site Mean, S.D.*	*101.0, 19.8*	*4040.0, 792.0*	*629.1, 109.0*	*25.2, 4.3*
Red Zone South 1	72	2880	362.8	14.6
Red Zone South 2	41	1640	169.6	6.8
*Site Mean, S.D.**	*56.5, 22.0*	*2260.0, 876.9*	*266.2, 136.6*	*10.7, 5.5*
Hoseland 1	120	4800	1128.0	45.1
Hoseland 2	118	4720	824.1	33.0
*Site Mean, S.D.**	*119.0, 1.4*	*4760.0, 56.6*	*976.1, 214.9*	*39.1, 8.6*
Thiaumont Platform 1	131	5240	1508.7	60.4
Thiaumont Platform 2	215	8600	2167.0	87.3
*Site Mean, S.D.**	*173.0, 59.4*	*6920.0, 2375.9*	*1837.9, 465.5*	*73.9, 19.0*

* Standard Deviation from the mean values at the two sites

Table 7: Crater disturbance dimensional (depth) data based on sample data from five sites on the Verdun battlefield

Site Name	Mean Crater Depth (cm) *(S.D.)**	Min Crater Depth (cm)	Max Crater Depth (cm)
Etraye 1	53.4, *32.2*	12	166
Etraye 2	53.2 *46.9*	10	212
*Site Mean, S.D.***	*53.3, 0.1*	11.0, 1.0	189.0, 32.5
Red Zone North 1	52.4 *28.6*	10	112
Red Zone North 2	40.3 *23.8*	10	144
*Site Mean, S.D.***	*46.4, 8.6*	10.0, 0.0	128, 22.6

Table 7 (cont'd)

Red Zone South 1	46.4 *17.0*	12.0	90.0
Red Zone South 2	30.2 *16.5*	10.0	72.0
*Site Mean, S.D.***	*38.3, 11.5*	11.0, 1.4	81.0, 12.7
Hoseland 1	40.1 *24.2*	10.0	236.0
Hoseland 2	47.0 *27.8*	10.0	136.0
*Site Mean, S.D.***	*43.6, 4.9*	*10.0, 0.0*	*186.0, 70.7*
Thiaumont Platform 1	98.2 *42.3*	14	300
Thiaumont Platform 2	96.3 *45.7*	16	330
*Site Mean, S.D.***	*97.3, 1.3*	*15.0, 1.4*	*315.0, 21.2*

* Standard deviation and mean generated from specified site

** Standard deviation and mean generated from combined between the two site averages

Table 8: Crater disturbance dimensional (area and volume) data based on sample data from five sites on the Verdun battlefield

Site Name	Mean Crater Area (m^2) *(S.D.)**	Max Crater Area (m^2)	Min Crater Area (m^2)	Mean Crater Volume (m^3) *(S.D.)**	Max Crater Volume (m^3)	Min Crater Volume (m^3)
Etraye 1	8.5 *7.2*	35.5	0.9	386.3 *604.2*	3267.2	6.1
Etraye 2	8.6 *7.0*	39.6	1.2	418.0 *708.3*	3590.0	8.2
*Site Mean, S.D.***	*8.5, 0.1*	*37.6, 2.9*	*1.1, 0.2*	*402.2, 22.4*	*3428.6, 228.3*	*7.2, 1.5*
Red Zone North 1	6.4 *4.6*	21.8	0.6	268.7 *311.4*	1236.7	3.2
Red Zone North 2	6.1 *4.5*	30.0	0.7	188.7 *315.3*	2521.6	4.2
*Site Mean, S.D.***	*6.2, 0.1*	*26.0, 5.9*	*0.7, 0.1*	*228.7, 56.6*	*1879.2, 908.6*	*3.7, 0.8*
Red Zone South 1	5.0 *2.0*	10.4	1.7	144.7 *95.0*	403.0	14.4
Red Zone South 2	4.1 *2.8*	10.7	0.5	95.8 *108.6*	370.2	2.7
*Site Mean, S.D.***	*4.6, 0.6*	*10.6, 0.2*	*1.1, 0.8*	*120.3, 34.6*	*386.6, 23.2*	*8.6, 8.3*
Hoseland 1	9.4 *7.0*	50.3	0.5	217.4 *232.6*	1383.1	9.4
Hoseland 2	7.0 *5.2*	33.1	0.4	233.9 *326.2*	2377.4	5.1

Table 8 (cont'd)

*Site Mean, S.D.***	*8.2, 1.7*	*41.7, 12.2*	*0.4, 0.1*	*225.7, 11.7*	*1880.3, 703.1*	*7.3, 3.0*
Thiaumont Platform 1	11.5 *10.3*	52.6	0.7	880.7 *992.8*	5253.7	7.2
Thiaumont Platform 2	10.1 *9.1*	60.7	1.2	923.4 *887.3*	5573.3	6.6
*Site Mean, S.D.***	*10.8, 1.0*	*56.6, 5.7*	*0.9, 0.4*	*902.1, 30.2*	*5413.5, 226.0*	*7.0, 0.4*

* Standard deviation and mean generated from specified site
** Standard deviation and mean generated from combined between the two site averages

Etraye

The far northern (Etraye) study plots are on the outside fringes of the Verdun battlefield (Figures 20, 21). The average crater disturbance coverage for the two plots was 20.3%, or about 1/5 of the plots' area (Table 6). The area was most likely shelled toward the very end of WWI when the Americans were driving the Germans out of the area. Not only is this an area where the armies were not in close proximity to the front lines of the main battle, but also an area that did not experience the stalemate conditions associated with areas further south on the battlefield. No trenches were observed at the Etraye site, which supports the assumption that stagnant conditions did not exist and troop movement through the area was fairly rapid. Artillery disturbance may have only occurred when the American forces shelled the ridges prior to launching offensive operations.

Because the study plots are situated on the upper shoulder of a ridge facing to the south, the magnitude of disturbance is greater than if the study plots were placed on the opposite side - the ridge's north-facing slope (Figure 26). I observed that on north-facing slopes on the Verdun battlefield, little to no disturbance was noticeable.

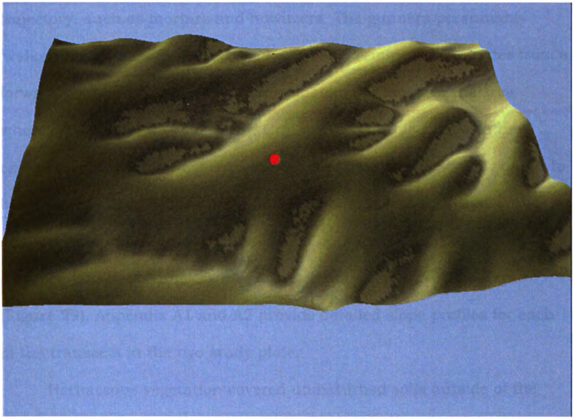

Figure 26. Due north-facing, oblique view of Etraye study plots and surrounding area. Vertical exaggeration is 3.0 and the area is 4X3 km.

Craters within each of the Etraye study plots are widely spaced, although I recorded several clusters of craters within the two plots (Figures 27, 28). The clusters contain craters that are slightly more spherical and deeper than other surrounding, individual craters. For example the maximum crater volume in these plots exceeds 3000 m^3 (Table 8), approaching volumes in the most heavily disturbed area at Thiaumont. While several of these larger craters existed in the plots, they were the exception rather than the rule, with smaller craters approaching the mean volume of ~400 m^3 being much more common. These common, small craters likely came from artillery that fired rounds at a high trajectory, such as mortars and howitzers. The gunners presumably 'walked' the rounds forward, based on pre-determined coordinates from a forward observer, thereby producing clusters of craters in the area where artillery fire was called for. Crater depth at this site, with the exception of the larger artillery rounds, is limited by the shallow depth to bedrock. The Etraye area contains thin Rendzina-like soils that are shallow to pure limestone bedrock; each crater penetrated only a small distance into the bedrock, with an average depth of 0.5-1.0 meters (Figure 29). Appendix A1 and A2 provide detailed slope profiles for each of the transects in the two study plots.

Herbaceous vegetation covered undisturbed soils outside of the craters but often did not occupy areas within the crater (Figure 30). In some deeper craters, close proximity to the water table lead to hydric conditions, preventing the colonization of crater bottom by surrounding vegetation at the study site. The majority of the soil surface between the craters is undisturbed and contains trees that pre-date the war, thus providing further evidence the area was only lightly disturbed.[13]

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[13] Pre-war trees were easily observed because, besides their larger size compared to other surrounding trees, they often grew in contorted forms and were heavily scarred from artillery shrapnel.

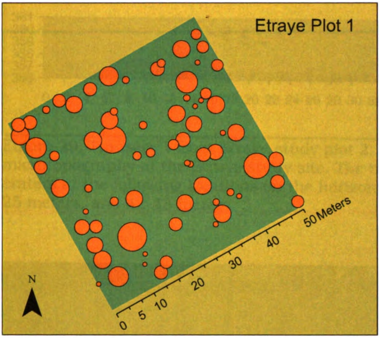


Figure 27. Crater disturbance patterns on study plot one, Etraye study site. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

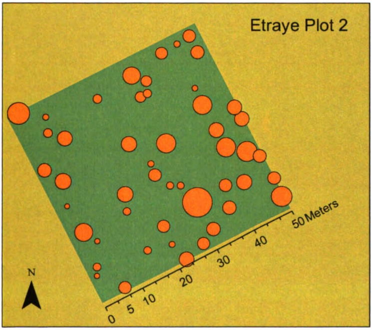


Figure 28. Crater disturbance patterns on study plot two, Etraye study site. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

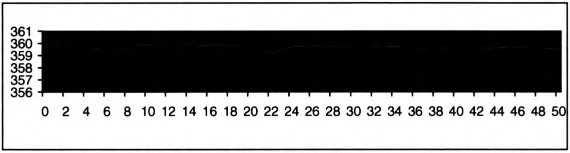


Figure 29. Transect 1 from Etraye study plot 2, as an example of surface microtopography at the Etraye study site. The transect shows three craters at the following locations on the horizontal axis: 4-9 meters, 20-25 meters, and 42-43 meters.

Figure 30. Crater cluster within the Etraye study plots at the Verdun, France battlefield. Note the paucity of vegetation in crater bottoms. Source, Author's collection, September 2004

Red Zone North

The Red Zone North plots are located on what was French territory prior to the battle, in close proximity to where the opening phases of the battle took place on February 21st, 1916. Shelling at this location was heavy, yet the German offensive moved through the area fairly rapidly following the bombardment, sparing the area months of constant shelling. Several trenches and *Stollen* (underground German bunkers) were observed in the vicinity, which suggests that the Germans 'dug in' for long-term occupation of the area after pushing out the French in the opening phases of the battle. Because of the south-facing location of the study site (Figure 31), it may have received German artillery fire at the outset of the battle and then received shelling from French artillery after the Germans became entrenched in the area.

Cratering at this location is fairly heavy and undisturbed patches of soil are not extensive. Approximately 25% of the surface in the plots is disturbed (Table 6), with a conservative average estimate of 2380 craters km^{-2}. Crater counts in this plot are conservative compared to the probable actual number of craters, due to the herbaceous ground cover and grasses (~50 cm in height), which obstructed the view of many craters.

Craters are scattered in a random pattern, although again, as at Etraye, there are several clusters of craters within the plots (Figures 32, 33). In some places, smaller craters were found inside larger craters, as seen along a typical microtopographic survey transect line (Figure 34). Appendix A3 and A4 provides the slope profiles for each of the transects in the two study plots.

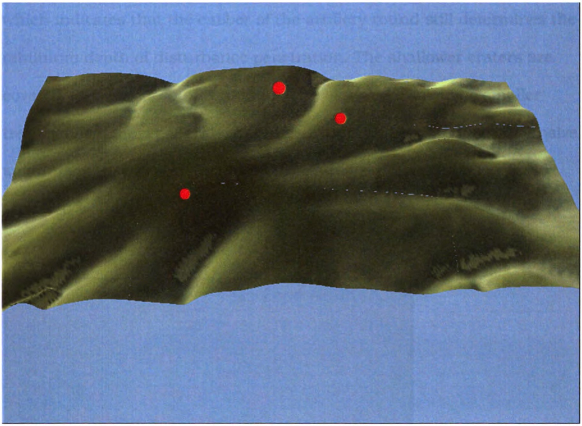


Figure 31. Due north oblique view of (from top of image down) Red Zone North, Red Zone South, and Hoseland study plots, and surrounding area. Vertical exaggeration is 3.0 and the area is 4X3 km.

The craters in Red Zone north are also fairly deep and steep sided when compared to the shallower craters at Etraye. The soils at this location are Hapludalfs (calcic brown soils, French Classification), which implies that they are thicker and better developed than the thinner Rendzina soils found at Etraye. The thicker soil, i.e. layer of unconsolidated materials, allowed the artillery explosions that created the craters to penetrate deeper before encountering bedrock, which would have limited the depth of the blast. Nonetheless, some of the smaller, shallower craters only dent into the upper portions of the soil, which indicates that the caliber of the artillery round still determines the minimum depth of disturbance penetration. The shallower craters are covered with herbaceous vegetation, grasses, and even some smaller trees, while the deeper craters are filled with leaf litter and lack extensive amounts of growing vegetation. No trees that pre-date the war were observed in the study plots.

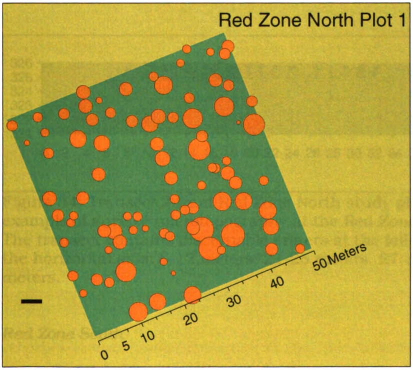


Figure 32. Crater disturbance patterns on study plot one, Red Zone North study site. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

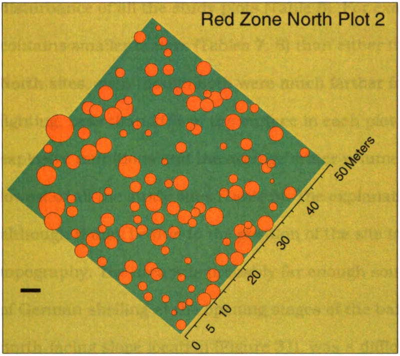


Figure 33. Crater disturbance patterns on study plot two, Red Zone North study site. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

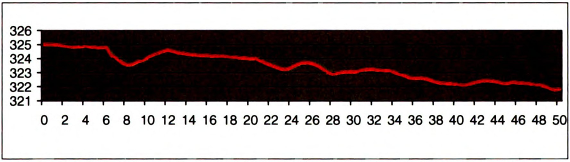


Figure 34. Transect 2 from Red Zone North study plot2 as typical example of surface microtopography at the Red Zone North study site. The transect contains discernable craters at the following locations on the horizontal axis: 6-12 meters, 21-25 meters, 27-31 meters, and 39-42 meters.

Red Zone South

Red Zone South, although further south than the previous two sites and therefore closer to the center of the fighting, contains the least disturbance of all the study plots (Table 6). For example, the site contains smaller craters (Tables 7, 8) than either the Etraye or Red Zone North sites, even though both were much farther from the center of the fighting. Less than 20% of the surface in each plot was disturbed by explosive munitions and the average crater volume of 120 m^3 is the lowest of all the study sites (Table 8). The explanation for this is unclear, although it may be due to the position of the site in relationship to the topography. The area was probably far enough south to escape the brunt of German shelling at the opening stages of the battle and, due to its north-facing slope location (Figure 31), was a difficult target for the French artillery.

Red Zone South is located close to a now removed narrow gauge railroad supply line (Figure 35). The rail line can be seen as a flat bottomed depression on the far right of the transect line in Figure 36. Numerous *Stollen* and trench works are in the vicinity of the rail line and the pattern on the crater plots (Figures 37, 38) suggests that the French gunners knew about the rail line and were able to observe some of the trench works. In WWI, if artillery gunners knew the location of a fixed target like a railroad line and had a forward observer to direct their fire, they would have been able to place artillery rounds in the vicinity of the target. The north side of plot one at this site runs parallel to the old rail line; this is where the majority of the craters are located. Other crater clusters are nearby the underground *Stollen* (Figure 37). The sparse cratering in plot two of the study site (Figure 38) occurs because this site was further from the *Stollen* complexes, although the north side of this plot runs parallel to the rail line as well. There were no *Stollen* in this plot and hence few craters, all of which suggests the French gunners had an idea of what they were firing at. In sum, the evidence provided by the cratering pattern at this site suggests that the area was under observation and the shells were not being fired blindly into a location with an unknown target. Rather, the craters here support the assumption that the artillery fire was directed at the *Stollen* complexes and the narrow gauge rail line.

Figure 35. Remains of a narrow gauge rail line in close proximity to Red Zone South study plots on the Verdun, France battlefield. Source: Author's collection, September, 2004.

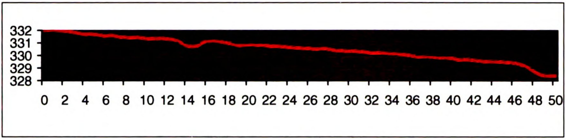


Figure 36. Transect 2 from Red Zone South study plot two, as typical example of surface microtopography at the Red Zone South study site. The transect shows one discernable crater at the 13-15 meter mark along the horizontal axis. The drop off on the far right is the edge of a former narrow gauge rail line.

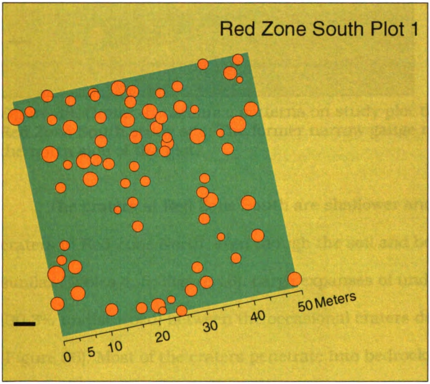


Figure 37. Crater disturbance patterns on study plot one, Red Zone South study site. The former narrow gauge rail line runs along the north side of the plot.

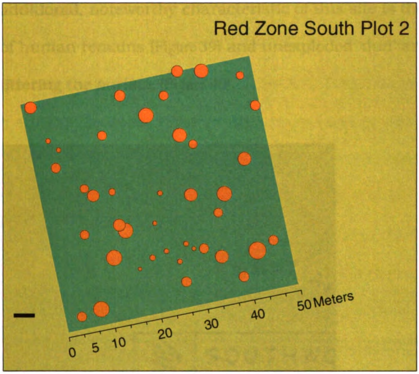


Figure 38. Crater disturbance patterns on study plot two, Red Zone South study site. The former narrow gauge rail line runs along the north side of the plot.

The craters at Red Zone South are shallower and smaller than the craters in Red Zone North, even though the soil and bedrock types are similar (Tables 4, 5; Figure 16). Large expanses of undisturbed soils exist (90.3% undisturbed) between the occasional craters denting the surface (Figure 36). Most of the craters penetrate into bedrock and have large amounts of leaf litter and other forms of decaying herbaceous debris filling in the bottoms. The main forms of disturbance are the rail line and the craters found in proximity to it as seen in figure 36 and the figures in Appendix A5 and A6. Due to the light disturbance, several trees that pre-date the wars exist at this site, mostly in the less disturbed plot two. An additional, noteworthy characteristic of this site is the numerous forms of human remains (Figure 39) and unexploded 'dud' artillery rounds found littering the surface (Figure 40).

Figure 39. Possible human femur bone remains found on surface within Red Zone South study plots on Verdun, France battlefield. Source: Author's collection, September 2004.

Figure 40. Author holding one of many unexploded munitions littering surface at Red Zone South study plots on the Verdun, France battlefield. Source: Author's collection, September 2004.

Hoseland

The Hoseland site is located on high ground surrounded by ravines and ridges of lower elevation (Figure 31). This topographic position made it a highly desirable one for both armies, and therefore a hotly contested location. In addition, the site is just off the crest - facing slightly to the south - so it was an easy target for the French artillery gunners. The study site has the wettest soils of the four. A perched water table is present due to the marl-type limestone that is sequenced above an aquitard layer of highly impermeable clay-rich shale, was present at the time of sampling (Setember, 2004) (Montagne 2003). Here, the limestone contains a high amount of silt, lowering its permeability, and is situated over the still less permeable layer of bedrock, leading to perched water conditions.

Disturbance, in the form of large intertwined crater complexes, at this location covers from over a third (Plot 2, 33.0%) to nearly half (Plot 1, 45.1%) of the soil surface (Table 6). Clusters of several large craters coalesced into one large crater complex are numerous; often smaller craters dent the larger craters within the complexes (Figures 41, 42). At the time of sampling (September, 2004), many of the craters were filled with water, thereby making crater counts in some of the complexes difficult for two reasons. First, the water in some of the crater bottoms was so high that the crater could not be entered for proper measurement. Secondly, when crater bottoms could be entered, the water covering the bottom obscured the individual craters within the complex in part due to the perched water conditions and frequent standing water within the craters (Figure 43); individual craters have since filled in with sediment, becoming large, shallow, crater complexes. While the average crater depth for the two locations was 43.6 cm (Table 7), very few craters exceeded 50 cm in depth and many were less than 40 cm deep.

The crater complexes at the Hoseland site have a curving, sinuous oval-like pattern and often link up with other crater complexes, surrounded only by islands of trees. I was rarely able to measure the individual craters within these complexes. Instead, the collection of individual craters within the complex was measured together as one large 'super crater'. For example, in plot one at this location, the crater with the maximum area of 50.3 m^2 (Table 8) is not an individual crater, but instead a complex of many craters that have merged.

Surrounding the many water-filled, crater complexes are islands of small stunted trees growing out of the crater hummocks[14] (Figure 43). As stated earlier, disturbance at this location was so heavy that counting the actual number of craters proved difficult and the amount of disturbance recorded in Tables 6 and 7, along what is shown in figures 41 and 42, should be considered a minimum estimate of the actual

[14] The name *Hoseland* was assigned to this site because of the strange, twisted, hose-like appearance of the trees growing out of the hummocks dividing the craters as seen in figure 30. For lack of a better term, this name stuck and the site received its "official" name.

degree of disturbance. A better representation of the surface disturbance can be seen in Appendix Figures A7 and A8, or the typical transect provided in figure 44, where individual craters as well as the large, shallow crater complexes tens of meters across can be observed in cross-section. The surface is also noticeably more disturbed than those surfaces at the previous study sites to the north. For example, while the number of craters km^{-2} at Etraye, Red Zone North, and Red Zone south are 2380, 4040, and 2260 respectively, the number of craters km^{-2} , at Hoseland jumps is a much higher 4760 km^{-2}. Also, keep in mind that crater counts here are conservative at best and do not capture the true nature of ground disturbance. Many of the flatter areas are due to the area 'smoothing out' from years of constant flooding which fills the craters and flattens out the hummock crests.

With time, individual craters within the complexes will likely become less discernable and the area will contain large sinuous depressions divided by hummocks that contain the main woody vegetation. However, with more time, these depressions may fill in with material in the hummocks and the areas could 'flatten out' and return to something approaching its original state. In sum, this is a process that I see in the future flattening the surface, and thus reverting the surface back to its original stat.

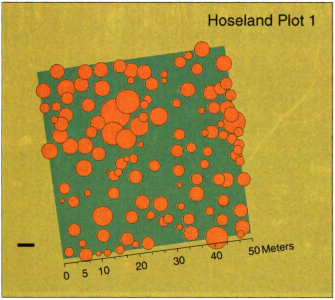


Figure 41. Crater disturbance patterns on study plot one, Hoseland study site. Crater counts on this plot are, at best, conservative and do not represent the actual number of craters within the plot. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

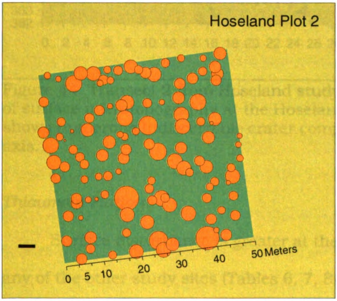


Figure 42. Crater disturbance patterns on study plot two, Hoseland study site. Crater counts on this plot are, at best, conservative and do not represent the actual number of craters within the plot. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

Figure 43. Stunted tree growth among water filled craters at the Hoseland study plot on the Verdun, France battlefield. Source: Author's Collection, May 2003

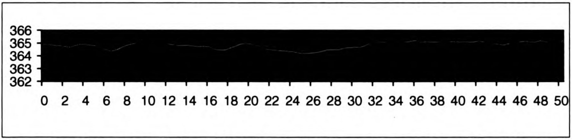


Figure 44. Transect 2 from Hoseland study plot one, as a typical example of surface microtopography at the Hoseland study site. The transect shows numerous indiscernible crater complexes along the horizontal axis.

Thiaumont Platform

Surface disturbance is greater at the Thiaumont Platform than at any of the other study sites (Tables 6, 7, 8). The size of the craters as well as the area of disturbance clearly shows that this study site contained the highest amounts of disturbance (Table 6, 7, 8). The site is on high ground (Figure 45) near the terminal limit of the German advance, where stalemate conditions prevailed throughout most of the battle. Three forts, part of the *Place de Verdun* (Fortress of Verdun), exist in the vicinity: Fort Souville, Fort Douaumont, and Fort Vaux, along with numerous fortifications on the Thiaumont Platform (Figures 12, 20). These fortifications were all highly contested and were continual targets of both the French and German heavy artillery (Figure 46). Massive craters from 420 mm and 380 mm siege guns, each exceeding 10 meters in diameter, blanket the platform and surrounding area. Disturbance in this area was so complete that after the battle, no trees were left standing (Horne, 1993). Historical documentation of the complete deforestation is supported by data on forest destruction following WWI (Graves 1918). Contemporary signs of forest cover destruction are also evidenced by the stunted, shrublike vegetation that has grown in place of the pre-war forests. No areas of undisturbed soil remain, and bedrock is often deeper than 10 meters, due to the millions of artillery shells that pulverized the surface over months of fighting (Montagne, 2003). The original micro and meso topography of the surface of the Thiamont platform has literally been completely altered by these millions of artillery rounds. The area has remained unforested because it is part of the Thiaumont memorial and therefore kept in herbaceous vegetation by frequent mowings and other forms of landscape maintenance. Small pockets of wetland vegetation occupy some of the craters, many of which contain standing water throughout the year (Figure 47). The unforested parts of the

Thiaumont Platform were chosen for study because the forest vegetation surrounding the vicinity of the memorial is so thick that movement in it is next to impossible.

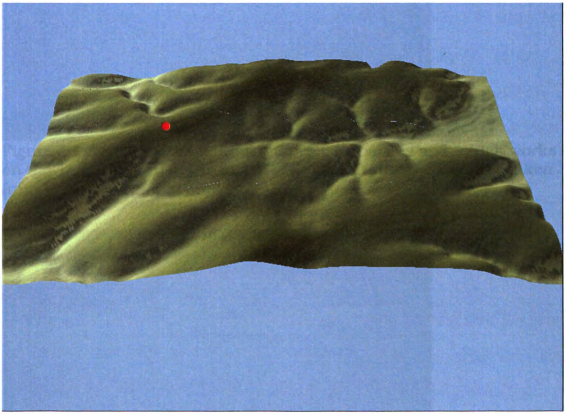


Figure 45. Due north view of Thiaumont Platform study site (red dot). Vertical exaggeration is 3X and the area is 6X4 km.

Figure 46. Aerial image showing crater disturbances and trench works on the Thiaumont platform in 1916. Source: Authors collection, taken from Verdun memorial museum.

Figure 47. Cattails (Typha spp) growing in water-filled crater at the Thiaumont Platform site on the Verdun, France battlefield. Source: Author's collection, September 2004.

Obtaining a count of the actual number of craters, along with crater dimensions, on the Thiaumont study plots proved impossible due to the shear number of craters and the swampy conditions in the bottoms of many craters and crater complexes. The crater disturbance plots in Figures 48 and 49 may, therefore, be misleading because no original remnants of the surface remain. The entire study site, along with the remainder of the platform, is one mass of interconnected crater complexes. Large depressions, with multiple craters within them ('Super Crater' complexes), are often divided by uneven hummocky ridges (Figure 50). By definition, a super crater complex is one that is a large depression exceeding 10 m in diameter that contains larger craters exceeding five meters in diameter, with smaller craters within the larger craters in the complex.

As with the crater complexes at the Hoseland study site, the large crater volumes here do not represent individual craters, rather they are volumetric estimates of many large craters within the 'super crater' complexes. Crater counts in plot two are higher only because less of the plot's craters were under standing water and therefore more accessible for sampling; plots one and two were 60 and 87 percent disturbed, respectively (Table 6). Surface disturbance at both of the study plots should actually register 100%, since no undisturbed area of the surface is remaining. The recorded disturbance is based on discrete craters that I was able to identify and measure. Dividing the craters are large hummocks with small craters denting even their surfaces. Although I tried to count each crater in each plot, the results indicate that a true crater count was not achieved.

A better representation of the surface disturbance at the Thiaumont study site can be seen in the transect line, taken from plot one (Figure 51). Figure 51 shows that the original surface has been completely altered and craters are separated only by uneven hummocks. Appendix figures A9 and A10 provide the slope profiles for each of the transects in the two study plots.

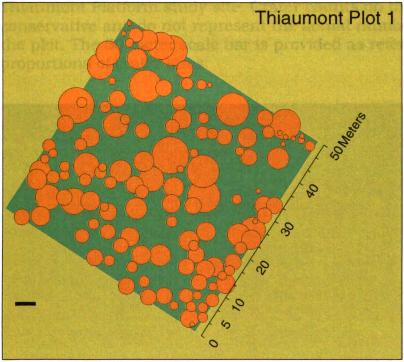


Figure 48. Crater disturbance patterns on study plot one, Thiaumont Platform study site. Crater counts on this plot are, at best, conservative and do not represent the actual number of craters within the plot. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

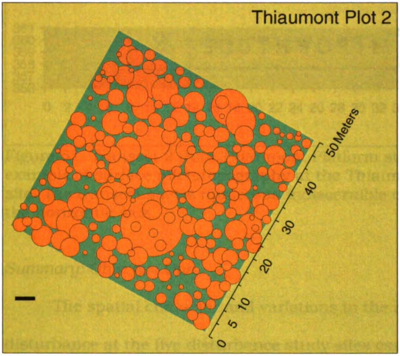


Figure 49. Crater disturbance patterns on study plot two, Thiaumont Platform study site. Crater counts on this plot are, at best, conservative and do not represent the actual number of craters within the plot. The 50 meter scale bar is provided as reference to differences in proportions of crater sizes.

Figure 50. Craters and hummocks dividing multiple crater complexes at Thiaumont Platform study site on Verdun, France Battlefield. Source: Author's collection, September 2004.

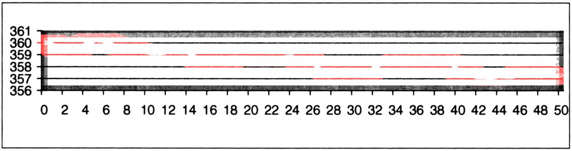


Figure 51. Transect 2 from Thiaumont Platform study plot one as typical example of surface microtopography at the Thiaumont Platform study site. The transect shows numerous indiscernible crater complexes along the horizontal axis.

Summary: Objective One

The spatial character and variations in the magnitude of disturbance at the five disturbance study sites can be attributed to the following four variables: (1) location of armies in relation to the front, (2) degree of stagnation, (3) topographic location of armies, and (4) geologic characteristics of the site. The variables that exerted the most influence on the magnitude of disturbance were the location of armies in relation to the fighting (front lines), and the degree of stagnation in terms of the battle itself. For example, Etraye received very little disturbance due to its location being far from the center of fighting and the fluid nature of movement when disturbance occurred in the area. Red Zone North, although somewhat removed from the center of fighting, had a reasonably high amount of disturbance due to the heavy artillery barrages it received when the battle opened on February 21st, 1916. Red Zone south was closer to the center of fighting but its topographic location likely prevented it from receiving the disturbance that the other areas in the vicinity were subjected to. Hoseland is located on a piece of high ground and was, therefore, a target for artillery. Craters at this location, due to the presence of standing water in crater bottoms for most of the year, have merged together into large, shallow crater complexes. Finally, Thiaumont Platform, the most disturbed of all the sites, was a highly contested area where stagnant conditions persisted through months of fighting. Crater counts at this location, as at Hoseland, were extremely high, and yet represent minimum disturbance estimates. Counts were difficult to obtain due to the near total disturbance of the study sites. In summary, both the crater plots and the transect data show that disturbance magnitude differs predictably among the five sites, and a spatial examination of their distribution within the study plots clearly helps understand the dynamics of the battle and how it relates to the variables of disturbance.

Objective Two

The results stemming from research objective one (above) focused on the disturbance characteristics of the soilscape 88 years after disturbance, and the variables that contributed to that disturbance. In this section I will report the data associated with my second research objective, which centers on soil development in those disturbed portions of the battlefield. I will focus this discussion on soil development within and near craters, around three main topics:

(1) How soil development differs within the crater proper, through a comparison of soil development on the crater side vs. the crater bottom;

(2) How the developmental pathway of soils within craters differs in kind from undisturbed soils adjacent to the crater

(3) How much soil development has occurred in the past 88 years following initial disturbance, through a discussion of chemical and physical indicators of soil development.

I begin this section with pedon descriptions taken from crater bottoms and crater sides, as well as undisturbed sites at each of three study sites: Red Zone, Bois de Thill, and Etraye. I conclude the section with a discussion of analytical results meant to assess the degree of soil development within the craters and compare that to development in undisturbed soils adjacent to craters.

Soil Profile Descriptions

Three soils in and near craters at each of three study sites (Red Zone, Bois de Thill, and Etraye) were sampled and described (nine craters total). The craters at each study site were selected to be representative of typical small, medium, and large craters at that particular site (Table 9). Smaller and larger craters were always present at each of these sites, but were not deemed representative of the typical range of crater sizes. Detailed descriptions of all nine pedons are reported in Appendix B. In the discussion below, each study site is discussed according to the order in which it was sampled.

Table 9: Dimensions of, and soil type within, excavated craters on the Verdun, France 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	232	256	38	Calcic Brown
Red Zone 3	396	402	59	Calcic Brown
Bois de Thill 1	430	352	52	Psuedogley
Bois de Thill 2	396	362	44	Psuedogley
Bois de Thill 3	276	282	36	Psudogley
Etraye 1	356	320	57	Rendzina
Etraye 2	470	474	103	Rendzina
Etraye 3	472	476	104	Rendzina

Red Zone

Soils at this study site are well drained and support mainly European Beech forest. The soils are thicker than most soils in the study area, and classify as Calcic Brown Soils (French Classification System). Crater bottoms have accumulated large amounts of leaf litter, branches, and other forms of organic, forest debris (Figure 52). Within the craters, a thick layer of unaltered leaf litter, usually ~10 cm of thickness, has accumulated on the soil surface. Generally, the combined thicknesses of the O and A horizons are greater on the crater bottoms compared to the crater sides and undisturbed soils (Figure 53). The thicknesses of the O horizons on the crater sides are usually approximately half (~6 cm) of those on the crater bottoms; the O horizons on the undisturbed soils are approximately 4 cm thick (Appendix B).

Figure 52. Excavation of crater two at the Red Zone soil development study site. The crater, as with other craters at the site, contains large amounts of forest litter in the form of branches and leaves. Source: Author's collection, September 2004.

A sharp boundary exists between the O horizons and the A horizons within soils in the crater bottoms, sides, and undisturbed soils. The boundary between the O and A horizons for each of these pedons in all three craters was either abrupt/smooth or clear/smooth (Appendix B). The distinctness of the boundary, although not apparent in the Appendix data, is stronger in the craters than in the undisturbed soils (Figure 53). The A horizon in the undisturbed soils occasionally contains lenses of limestone gravel channers in its lower portion. The gravel layers are a likely result from ejecta thrown from the nearby crater at the time of disturbance.

Figure 53. Profile of excavated crater (crater one) at Red Zone soil development study site. Note thick O and A horizon in the crater bottom. Crater bottom is at top-center of the image where the orange measuring tape is located. Source: Author's collection, September 2004.

Now after 88 years of bioturbative activity and forest litter cover, the gravel has been incorporated into the soil profile. The gravel is now beneath the surface because organisms, such as earthworms, have a sorting effect on the soil, thus contributing towards horizon development (Johnson et al. 1987; Johnson et al. 2005; Whitford 1999). Continuing with earthworms as an example, the worms are able to move smaller particles upward as they track through the soil, but unable to move the larger clasts of gravel, thus the gravel that was thrown upon the surface has now been buried and incorporated into the soil column.

Gravel is also abundant in crater bottoms, and these coarse fragments generally increase in abundance and size with depth (Figure 54). For example, in the crater bottoms the O horizons contain no gravel, the A horizons 5-25% coarse fragments, and the C horizons 80-90% coarse fragments (Appendix B). Soils in the crater bottoms are weakly developed and either contain O and A horizons directly above weathered bedrock (now C horizon material) or contain a very weak B horizon, as was apparent in the third crater excavated at this study site. A weak B horizon exists within the third crater at the Red Zone site, as evidenced by its reddish color (10 YR 5/4). It also had developed moderate, fine, sub-angular blocky structure and firm consistency, as compared to the more yellow colored (2.5 YR 7/2) C horizon with its weaker structure (weak, fine to very-fine sub-angular blocky) and consistency (very friable) in the C horizon material below (Figure 55).

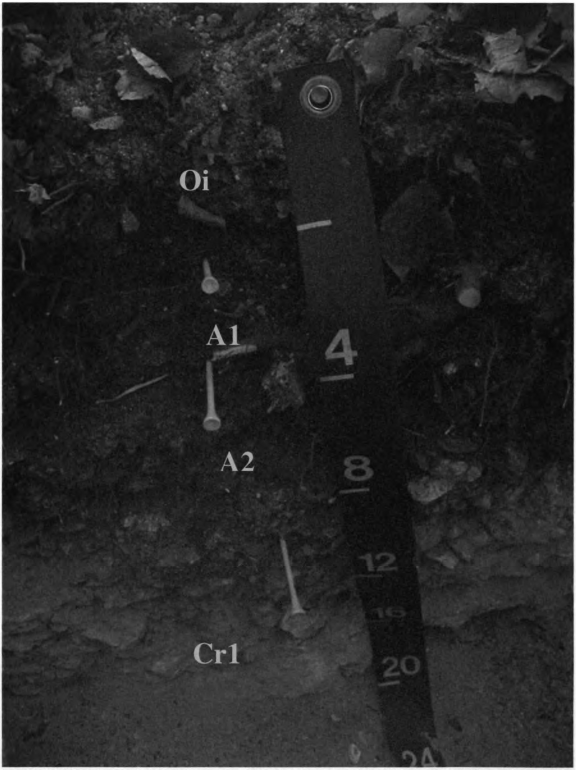


Figure 54. Soil in the bottom of crater one at Red Zone soil development study site. Note that coarse fragment content increases with depth. Source: Author's collection, September 2004.

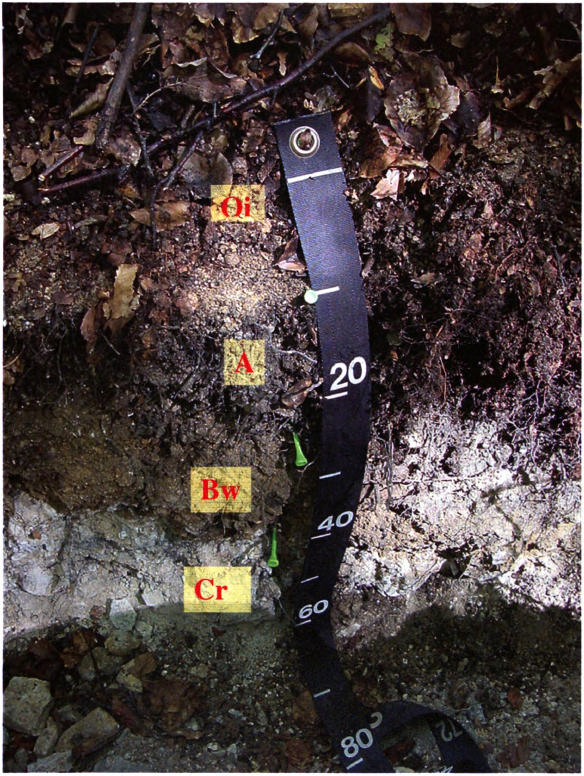


Figure 55. Weakly developed B horizon between 20 and 40 cm depth, in the bottom of crater three, Red Zone study site. Area beneath the 60 cm mark is in shadow. Source: Author's collection, September 2004.

The C horizon material within the craters at this site represents parent material that was once bedrock prior to disturbance 88 years ago. Now, the layer of soil that once protected the bedrock beneath from significant weathering and soil forming processes is gone, due to the artillery blast that exumed the sediments, thus forming the crater. Since the battle, the bedrock, now within the craters, has taken on a significantly weathered appearance and characteristics. The unweathered bedrock is hard limestone; material had to be chipped out with a geologic hammer for examination. In contrast, the weathered C horizon has a weathered saprolitic appearance and could be broken into smaller pieces without tools, manually. The saprolite also contained weathering rinds on bedrock clasts, which was broken down into clay with coarse fragments along the fracture lines. The weathered C horizon material grades gradually into unweathered bedrock with depth. The weathering seems to follow fracture lines in the limestone bedrock, probably generated from, or at least exacerbated by, the artillery blast.

Bois de Thill

Soils here are poorly drained with evidence of redoximorphic features (e.g. reddish areas where iron in the soil has been oxidized with mottles of grey where iron is in a reduced state) clearly evident throughout the profile (Figure 56). Poor drainage is a result of a seasonally high, unconfined water table and clay textures with low permeabilities. The heavy clay soils classify as Psuedogleys (French Classification System).

O horizons only rarely occur within the crater bottoms due to the extremely high amount of bioturbation, mainly earthworms, which act to incorporate the raw organic material into the mineral soil and thereby facilitate its breakdown. The high amount of earthworm activity at this site was surprising, considering the evidence of a high water table. Casts formed by the earthworm activity have led to the development of strong granular structure within A horizons at this site. The A horizon in each of the craters excavated is thickest in the centers of the crater bottoms, thinning as it approaches the crater side and the undisturbed adjacent soils on the nearby upland, where it is thin (~20 cm) and not as apparent (Figure 57; Appendix B). The undisturbed A horizons were not as dark and did not have the abrupt horizon break to the Cg horizon below like the A horizons in the craters (Figure 58; Appendix B). Instead, the A horizons would blend into the B horizon below them with no discernable break in the boundaries. Using crater 1 as an example, the thickness of the A horizon in the crater bottom was 24 cm, in the crater side the A horizon was 19 cm thick, and in the undisturbed soil it was 22 cm. The A horizon in the undisturbed soil was nearly as thick as, but it was not as dark (10 YR 3/2) as the A horizon in the crater (10 YR 2/1) as seen in Figure 57 and the data provided in Appendix B. Beneath the A horizons on crater bottoms are Cg horizons containing mainly oxidized iron concentrations in the upper portions and reduced iron concentrations in the lower profile. Depths to predominately reduced iron concentrations increases as distance from the crater bottom increases, i.e., up the crater sides. In the undisturbed soils, weak Bg horizons can be observed. Signs of redoxymorphic features are apparent in the C horizons as well.

The soils at the Bois de Thill site do not appear to be as developed as the soils at the Red Zone site. Horizonization boundaries are discernable by a color contrast that separates the darkly colored A horizons from the gleyed horizons below (Appendix B). Although there are earthworm casts that penetrate into the upper portions of the gleyed horizons, the poorly drained conditions at this site confine earthworm activity to the upper portions of the soil. The limited depth of earthworm activity is apparent not only in the color contrast between the horizons, but also by the structure of the soil, that changes from a moderate granular structure in horizon A to a moderate subangular blocky structure in the B and C horizons below (Appendix B).

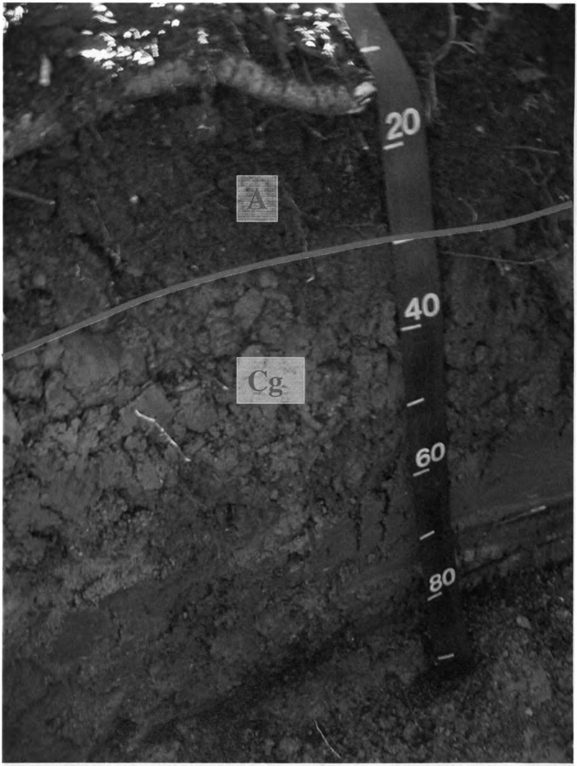


Figure 56. An A horizon overlying the redoxymorphic features in a Cg horizon, on crater side within crater one at the Bois de Thill soil development study site. Source: Author's collection, September 2004

Figure 57. Excavated trench in crater one at the Bois de Thill soil development site, displaying a thick A horizon over a Cg horizon. Boundary is situated at the 30 cm depth. Source: Author's collection, September 2004.

Figure 58. Undisturbed soil profile at Crater three, Bois de Thill soil development study site. The golf tee at the 20 cm depth indicates the boundary between the A and B horizons while the golf tee at the 55 cm mark indicates the boundary between the B and C horizons. Source: Author's collection, September 2004

Etraye

Soils at this study site are Rendzinas; they are shallow soils that developed out of a 'pure' limestone bedrock with little residium (Figure 59). The Rendzina soils at this site support mainly European Beech forest. In some of the deeper craters, standing water is present throughout most of the year due to a seasonally perched water table (French Forest Service, unpublished data). The craters I excavated and sampled were not influenced by the seasonal water table and contained only minimal amounts of redoxymorphic features (Appendix B). Due to the shallowness of the soils to bedrock, the depth of most of the craters is limited (Table 9), except for those stemming from large caliber artillery rounds. Large amounts of bioactivity, mainly from earthworms, had removed most of the organic material from the soil surface by the time of sampling. Worm casts and middens were omnipresent within the study area. An O horizon was observed within only two of the three crater bottoms (craters one and two). The O horizon thickness in these crater bottoms was five and four cm thick, respectively.

A horizons are thickest on the crater bottoms and are situated above a highly weathered C horizon comprised of fragments of limestone bedrock, clay peds, with tongues of organic matter extending down between fractures in the limestone bedrock. Using crater two as an example, the A horizon on the crater bottom is 28 cm thick, the Cr horizon below extends to 43 cm, below which lies mostly unweathered limestone bedrock (Figure 60). In craters one and two, no B horizon was recorded, the soil consisted of an A horizon above a highly weathered C horizon (Appendix B). In crater three, I noted a weakly developed B horizon that was apparent by its reddish color (10 YR 4/4) in comparison to the darker (10 YR 3/2) A horizon above and the more yellow colored (10 YR 5/6) C horizon below (Appendix B). Post-war bioactivity and percolation of water has led to thick tongues of organic material penetrating well into fractures in the limestone bedrock, likely associated with the effects of the artillery blast. Bedrock along the sides of these tongues of organic matter has weathered to a clay-like composition with embedded rock fragments ranging in size from small gravel to large cobbles. The fragments of rock generally increase in size moving down the profile.

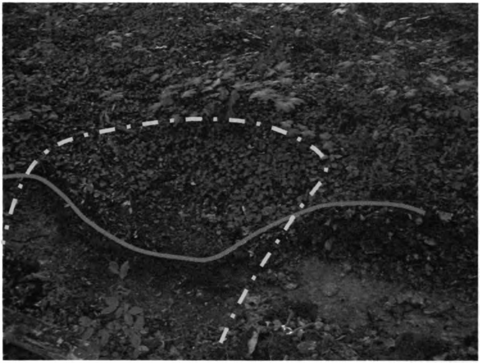


Figure 59. Trench (solid line profile) extending across crater one (edge defined by dotted line) at the Etraye soil development study site. Note the thin nature of the soil and lack of a B horizon. Also note thickness of A horizon within crater (left center of image).

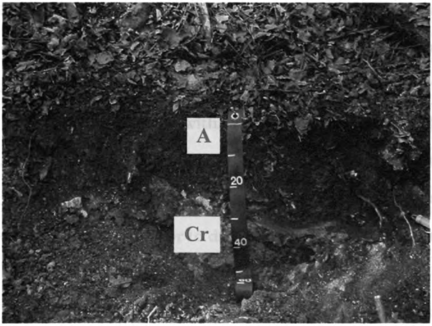


Figure 60. An A horizon above C horizon material (below 25 cm) that, before disturbance, was unweathered limestone bedrock, at crater two at Etraye soil development study site. Note the smeared clay (right of tape) indicating weathering of the former limestone bedrock to right of tape.

Summary: pedon descriptions

Soils within craters at each of the three study sites contained substantially darker A horizons than those undisturbed soils adjacent to the crater bodies. At most of the study sites, with the exeption of craters at Bois de Thill, the A horizons were also thicker in crater bottoms compared to the soils adjacent to the craters. Although the A horizons at Bois de Thill were thicker than on the crater bottoms, they were not nearly as dark and did not have the distinct boundary delineations as those soils within the crater. The A horizons were generally thickest at the crater bottom and thinned out progressing towards the crater rim. Organic horizons followed the same pattern as A horizons at the Red Zone site, but were generally absent at the Bois de Thill and Etraye sites. The lack of organic horizons at these two sites was likely due to the high amounts of bioturbation that rapidly incorporates the organic matter into the A horizon.

Soil development within craters at the Etraye and Red Zone sites was apparent by the development of an A horizon, several weakly developed B horizons in crater bottoms, and by the presence of a C horizon that once, prior to disturbance, unweathered limestone bedrock.

Lab Analysis

Texture

Soils from each of the three study sites contained large percentages of clay and had USDA textures that ranged from clay loam to clay (Appendix C). Soil textures at the Red Zone site were loamy (~50% sand, 25% silt, and 25% clay); soil textures at Bois de Thill fell within the clay textural class (~20% sand, 20% silt, and 48% clay); soils at Etraye ranged from clay loams (~25% sand, 45% silt, and 30% clay) to clays (~ 15% sand, 35% silt, and 50% clay). The thick O horizons on crater bottoms at the Red Zone site (and the crater bottom in crater three at Etraye) did not contain enough mineral content in the sample to for a particle size analysis to be performed at the 10 cm depth. Since the horizons at this depth contain mainly fibric organic material and little mineral material, they classified as Oi horizons, only organic carbon content and pH analysis were run on samples containing primarily organic matter. Soil textures were fairly uniform throughout each of the soil profiles and clay content shows little to no increase with depth (Figure 61). For example, at the Etraye site, craters two and three have soil textures that are classed as clay throughout the profile (with the exception of the undisturbed 50 cm depth in crater three). Clay content in each of these craters fluctuates randomly between 30 and 70 percent clay (Appendix C). At the Bois de Thill site, clay content in each of the craters is also relatively high, between 26 and 57 percent (Appendix C).

The 26% clay percentage is an anomaly, from a sample on one the crater bottoms that contained a lens of sandy material. Without this number, clay content actually ranges between 37 and 57 percent. Soils at the Red Zone site had the largest variance of textural classes and clay content. Clay content in these soils ranges from anywhere between 9 and 55 percent. Also apparent in Figure 61 is that the differences in clay content between the crater bottom, side, and undisturbed soil are random.

These data show that clay content is (1) a significant component of the parent material at each of the study sites, and (2) that translocation of clay particles is not significant enough to be measurable. I had originally speculated that an increase in clay content with depth would serve as an indicator of soil development. The depth plots in Figure 61 and the particle size data in Appendix C clearly illustrates that the parent material, in these instances, contains significant amounts of clay. A significant amount of clay would have to be translocated before any notable changes occurred. In addition, the calcium in the limestone also acts to retard lessivage (Duchaufour 1982). In clay rich soils such as these, this would probably take a much longer period of time than soils that consisted of coarser textured parent material.

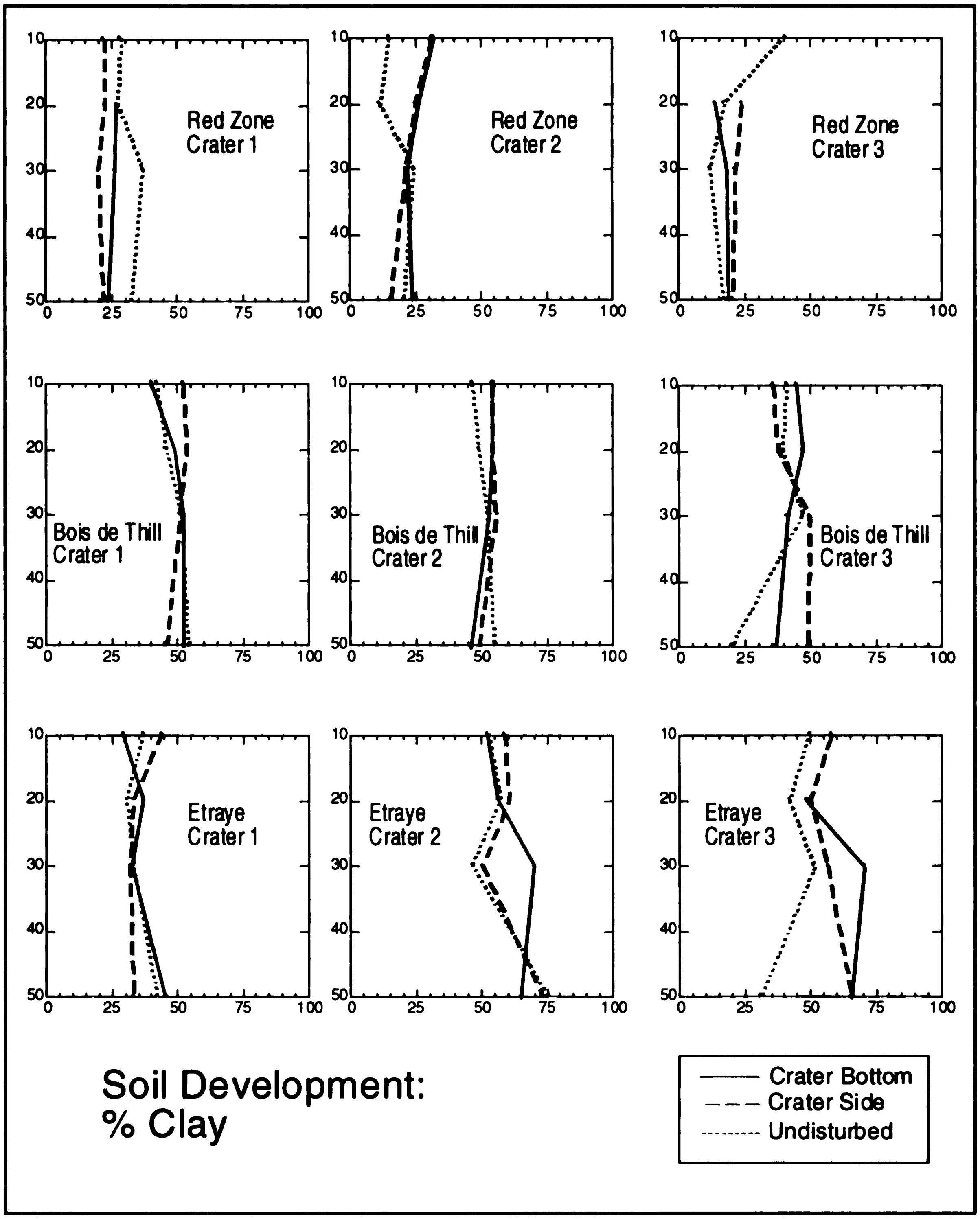


Figure 61. Verdun soil development as shown by the clay contents at sampled depths of 10, 20, 30, and 50 cm.

pH

Soil pH values increased with depth in each pedon sampled at the three study sites (Figure 62; Appendix D). This increase in pH with depth in the disturbed soils within the crater, as well as in undisturbed soils adjacent to the crater, indicates that a measureable amount of soil development, especially with regard to leaching and acidification, has occurred in the 88 years since disturbance. The pH of the undisturbed soils is generally lower (~0.5 pH) than the pH of the soils within the craters, indicating that the disturbed soils are not as developed or leached as are the undisturbed soils (Figure 62; Appendix D). At each study site the rate of change in soil pH with depth between the crater bottom, side, and undisturbed soils is fairly consistent.

Soil pH values at the Bois de Thill site are lower than the pH values at Etraye and Red Zone due to the more acidic nature of the parent material at Bois de Thill. For example, in the bottom of crater one at Bois de Thill the pH at 10 cm is 5.58 while the pH is 7.23 at 50 cm depth (Appendix D). In contrast, pH in the bottom of crater one bottom at Etraye is 7.38 while the 50 cm pH value is 7.56 (Figure 62; Appendix D). These differences in pH are attributable to the differences in parent material between the sites. Parent material at Bois de Thill is colluvium, consisting mostly of clayey sediment derived from the bedrock of the Woerve valley, whereas the parent material at Red Zone and Etraye is dominantly limestone residuum. While shale contains minerals that lean towards the acidic side of the Ph scale, the primary component of limestone, $CaCO_3$ is a mineral that is basic, resulting in much higher Ph values.

The change in pH with depth on both undisturbed soils and within craters is less at Etraye and Red Zone because the high clay contents and the limestone bedrock tend to buffer the changes in pH at the latter two sites. Nonetheless, the fact that pH changes this noticeably with depth in these highly buffered limestone soils is an indication that the basic cations weathered from the minerals that comprise the limestone are being leached out of the profile. The high concentrations of organic matter and focus of water movement in the crater bottoms likely contributed to the rapid lowering of pH levels in the upper portions of the soil profile. In locations where there was an organic horizon such as the craters at the Red Zone site, the organic matter contained a pH value that was around 7.0 (Appendix D). The neutral value of the pH in these organic horizons likely contributed towards lowering the pH values of the normally more basic pH values associated with a limestone soil (Schaetzl and Anderson 2005).

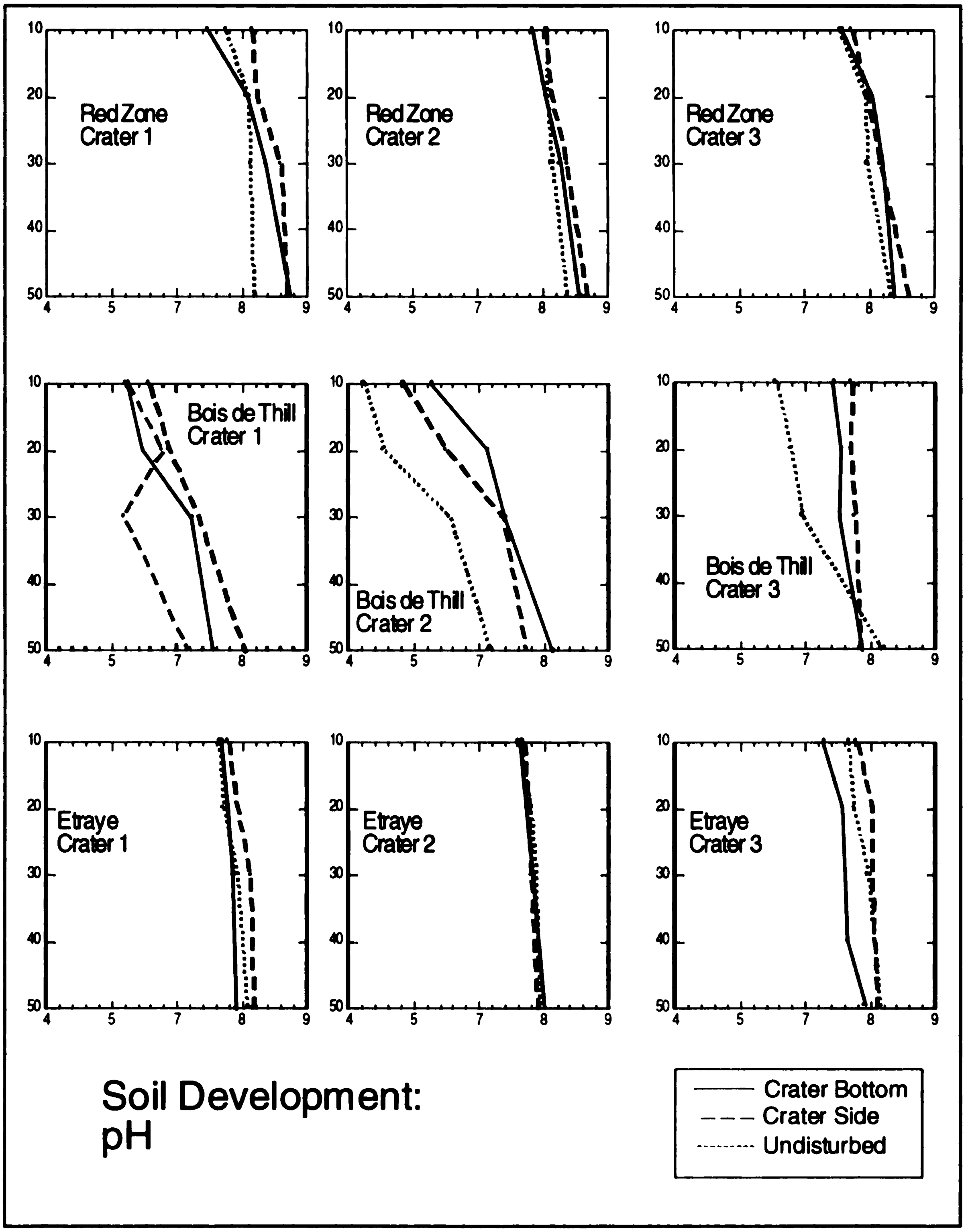


Figure 62. Verdun soil development as shown by pH levels at sampled depths of 10, 20, 30, and 50 cm

Organic Carbon

Organic carbon (OC) contents are significantly higher within crater soils when compared to undisturbed adjacent soils at each of the three study sites (Figure 63; Appendix D). In all but one crater (crater one at Etraye), the organic carbon contents are notably higher in the crater bottom soils than in the soils on the crater sides. The large spikes of organic carbon content in the upper reaches of the profile in the craters at Etraye and Red Zone are from samples taken from O horizons.

These OC data illustrate that significant amounts of organic matter are collecting within the crater bottoms at each of the study sites. These concentrations of OC show up as established organic horizons or as A horizons with significant amounts of OC. For example, the soils in each of the crater bottoms at the Red Zone site each contain an O horizon between 8 and 15 cm thick above an A horizon that extends at least another 15 cm in depth. At the Etraye and Bois de Thill sites, although an O horizon was not present (with the exception of craters one and three at Etraye), there was still a significantly higher amount of OC in the crater bottom when compared to the undisturbed adjacent soils. Not only does the development of O and A horizons serve to indicate the very beginnings of soil formation in formally exposed unaltered bedrock, but also that soil development on the crater bottoms is different than the adjacent undisturbed soils.

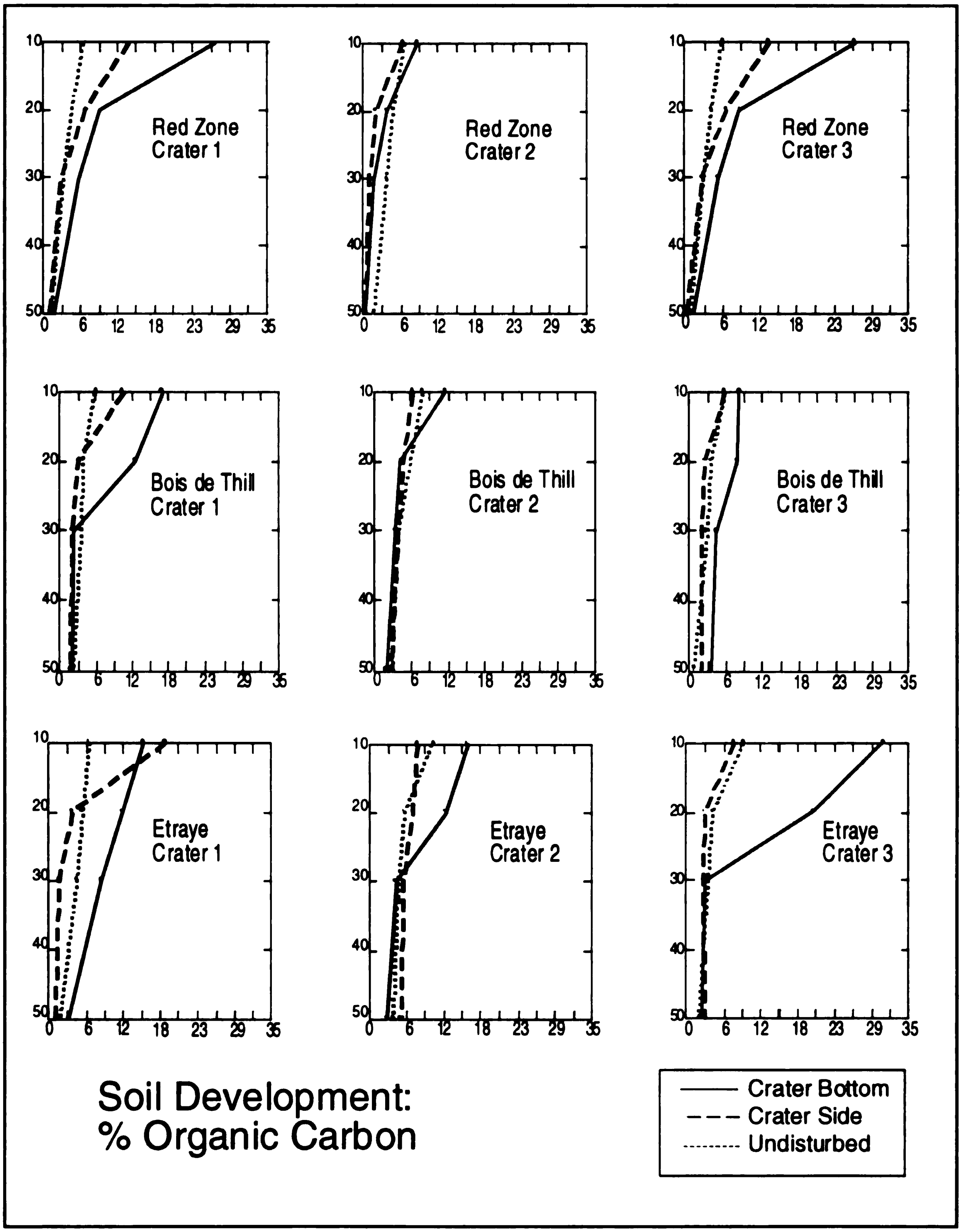


Figure 63. Verdun soil development as shown by organic carbon contents in soils at sample depths of 10, 20, 30, and 50 cm.

Elemental Ratios

The XRF analysis yielded a suite of data on elements from the sediments collected at each of the sample depths. As stated in my methods section, I used the percentages of the elemental data to construct ratios that reflect primary mineral weathering. This was done by comparing elements that reflect minerals in the soil that are highly resistant to weathering to those elements that represent minerals that are more easily weathered and 'washed out' of the soil profile by weathering and translocation. By using this ratio approach, at sample depths of 10, 20, 30, and 50 cm, horizons and pedons can be examined and compared to assess, in general, the amount of weathering that has occurred. Higher ratios presumably indicate more weathering.

Results from the XRF "weathering" ratios are mixed (Figure 64; Appendices D, E). Data are not available from several of the crater bottoms because the samples lacked ample amounts of mineral material with which to perform the XRF analysis. In this section I will discuss the Zr+Ti)/(Ca+Mg+K) elemental ratio. Other ratios that placed larger numbers of mobile elements in the denominator were constructed from the elemental values derived from the XRF procedure, (Appendices D, E), but the results were similar. Therefore, I have decided to report on this simpler ratio that contained elements commonly found in soils formed in limestone residuum.

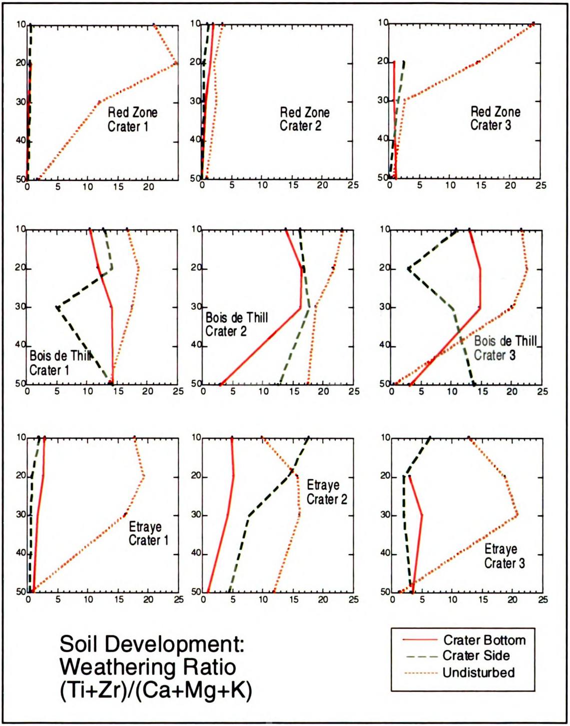


Figure 64. Verdun soil development as shown by the ratio (Ti+Zr)/(Ca+Mg+K) at sample depths of 10, 20, 30, and 50 cm.

The graphs in figure 64 reveal that, while a general decrease in weathering with depth does exist, several trend breaks or anomalies are apparent. For example, while soils at the Red Zone site had an overall trend of lower ratio values with depth, there are several breaks in this trend within the Etraye and Bois de Thill depth plots. Craters one and three at the Bois de Thill site have ratio values from the crater side that are higher at 50 cm depths than the ratio values at the top of the profile. Ratio values from the Bois de Thill site may have erratic patterns because the parent material is colluvium and not material weathered in situ from bedrock below, as is occurring at the Etraye and Red Zone sites. The colluvium consists of varying stages of weathered material brought in from higher elevations of the Meuse escarpment to the west.

The elemental ratio graphs (Figure 64) also illustrate that the undisturbed soils are more leached and weathered than are the disturbed soils within the craters. Excluding crater three at the Bois de Thill site, the undisturbed soils generally have higher ratio values than the soils within the crater. In addition, the undisturbed soils and disturbed soils within the craters start out with markedly different ratios, yet coalesce into nearly identical elemental ratios at 50 cm in the majority of the soil profile bottoms. The equifinality of the ratios suggests that these lower depths contain ratio values that reflect what the unweathered bedrock, now exposed as the surface of the crater bottoms, once contained. For example, craters at the Red Zone site contained ratio values at around 0.5 at the 50 cm depth (Appendix D). At this depth in the crater bottoms the bedrock was unweathered and reflects what was exposed immediately following the disturbance by explosive munitions.

As further support for limited weathering of the now exposed bedrock in the crater bottoms, the differences between the ratios at the top and bottom of the profile are not as large as are the ratios for the undisturbed soils (Figure 64; Appendices D, E). Using crater one from the Red Zone site as an example, the ratio difference between the 20 cm (0.69) and 50 cm (0.08) sample depth on the crater bottom is a mere 0.61. In contrast, in the undisturbed soil of this crater the difference in ratio values between the 10 and 50 cm depth is a much larger 19.42. Thus, although weathering is occurring within the crater bottom, the soils within the crater are nowhere nearly as weathered as the undisturbed soils adjacent to the crater. The lack of strong weathering in crater bottoms is apparent in the other depth plot trends at the Red Zone site (Fig. 62). (The trend is also somewhat apparent in craters one and three at the Etraye site (Fig 62).) Depth plots from the craters contain low ratio values while the undisturbed portions of the profile have much higher ratios, indicating higher amounts of weathering. Bedrock in the craters has only recently been exposed and has 'only' had 88 years of exposure to weathering processes. Nonetheless, weathering, leaching and acidification have occurred in the crater soils, indicating that after 88 years, measureable amounts of soil development are apparent.

Soil development processes

Pedon descriptions and the resulting data from the analytical procedures discussed above clearly indicate that some degree of soil development has occurred within the craters since the battle of Verdun. After the initial disturbance 88 years ago, there was likely no "soil" in the crater bottoms, only an exposed face of fractured limestone and rubble. Since that time, most of the newly exposed surfaces within the craters have developed thick accumulations of organic matter and the then-fresh bedrock has weathered somewhat. The early stages of soil development are indicated by a decrease in pH near-surface horizons (Figure 62; Appendix D), indicative of acidification, weathering and leaching.

Also indicative of soil development is the weathering of materials in the upper portions of the soil profile and their translocation within the profile, as indicated by the elemental ratio values generated by the XRF analysis procedure (Figure 64; Appendices D, E) and the formation of distinct O and A soil horizons in the crater bottoms. If these indicators of soil development are examined within the theoretical principles of the (Runge 1973) energy model, one could conclude that soil formation is largely driven by gravitational energy, *aka* water movement through the soil column.

The energy model,

$$\mathbf{S=f\,(o,\ w,\ t)},$$

assumes that soil development (S) is primarily a function of organic matter (OM) production (o), the amount of water available for leaching (w), and time (t). Infiltrating water is assumed to be the primary vector driving soil development. A comparison between soils in the crater bottoms and the 'control' undisturbed soils illustrate this point. The once unweathered bedrock on crater bottoms is now weathered and contains thick accumulations of humified organic matter above it. Over the years, the crater bottom has acted as a focal point for precipitation, forest litter, and eroded sediments from the soil surface. Not only does organic matter tend to concentrate in the crater depressions, but also water associated with precipitation events and snow melt. The concentrated movement of water percolates through the accumulations of organic matter and the energy of its movement tends accelerate the humification of that organic matter (Runge 1973). The bedrock in the crater bottoms has also experienced accelerated weathering due to the increased focus of water moving through the crater bottom (Figure 64). The organic matter that has been deposited in the joints of the bedrock and the organic complexes that result when the organic material is broken down by microbial activity help to chemically weather the bedrock. Water movement through the soil column has removed minerals that contributed to higher pH values. With the removal of these minerals, and the accumulation of organic matter, the pH values tend to lower or move closer to the neutral value of seven. The movement of water is also leaching the profile of soluble minerals which leads to the weathering of the soil from top down. In this regard, the gravitational energy associated with water in the Runge energy model clearly is driving soil development, and this type of development is preferentially stronger within the craters, where there is a focal point for water movement.

Other processes of soil formation not mentioned in the Runge model, such as bioturbation and microbial activity, have also largely contributed to soil development at the Verdun battlefield. The degree of horizonization, and the rapidity by which the soil horizons formed within the craters, would not have occurred as it did in the absence of key biopedoturbation processes. Worm activity is notable deep into the weathered C horizon material in crater bottoms. Tongues of organic matter, brought down by earthworms consuming surface litter, penetrate well into fractures within the C horizon. Clay weathering rinds surround the organic material brought down into these cracks. The litter that has accumulated on crater bottoms, when not subjected to high water tables, is shortly thereafter consumed by earthworms and incorporated into the soil profile. It can be argued that without this sort of activity in the craters, they would consist of a layer of leaf litter over a much less weathered bedrock. Instead the litter inside the craters is mostly broken down and incorporated into the weathered bedrock. Decomposed organic matter also produces organic acids that facilitate the breakdown of bedrock and the soil profile gradually thickens. In conclusion, it is the two processes of bioturbation and the gravitational energy of water that have shaped the course of soil development within these soils.

Bombturbation as a form of Pedoturbation

As the previous section has demonstrated, pedoturbation has strongly influenced soil development within the newly exposed material in craters. There are numerous forms of pedoturbation that stem from biologic or physical processes (Hole 1961; Johnson 2005; Whitford and Kay 1999). The majority of soil mixing is due to biological processes and these processes are either proanisotropic (horizon forming) or anisotropic (horizon mixing) (Johnson et al. 1987). Johnson, Domier and Johnson (2005) have defined four bioturbation process styles: upward biotransfers, biomixing, cratering, and soil/biomantle volume increases (Table 10). According to Johnson et al. (2005), through biotransfers and biomixing processes, conveyor belt and mixmaster organisms shape horizons through movement of materials in the soil. Cratering organisms, such as badgers, skunks, and humans, on the other hand, impact the surface and destroy soil horizons, thus leading to regressive pedogenesis. A large surface impact that removes a significant amount of surface material would expose enough unaltered parent material so that soil formation would be reset to $time_{zero}$, or the beginning of new soil formation.

Table 10: Bioturbation styles, organismic examples, and effects on soil properties (Modified from Johnson et al., 2005)

Bioturbation Process Styles	**Examples of Organisms**	**Effects on soils and sediments**
Upward biotransfers of fine-fraction and small gravels from the lower soil into the upper portions by *conveyor belt* or *moundmaker* organisms	some ants, worms, crayfish, clams, ground squirrels, badgers	Loosened, texturally anisotropic biomantle, contrasts between soil horizons, biologically driven particle size differentiation, surface mounds
Biomixing via *mixmaster* and *moundmaker* organisms that burrow, wriggle, mix, and/or churn material mainly within the soil	Moles, pocket gophers, myriad marine and terrestrial invertebrates, humans	Loosened, texturally anisotropic biomantle, contrasts between soil horizons, material from below biomantle brought to surface, surface mounds
Cratering and other *surface impacting* organisms (referred to as *crater makers*)	Badgers, pigs, birds, skunks, tree-uprooting, fish, humans	Surface craters, hollows, depressions, shallow licks, scratchings, scrapings, sediment burrow collars, surface rubble, spoil heaps, excavationss
Soil/biomantle volume increases by in situ organic movements, growth, bioagitations, and bioaccumulations that occur mainly within the biomantle, but also below it through the whole soil	Growth structures of plants, fungi, algae, and free living protocists, and bacteria	Loosened biomantle, soil microstructural features, biopellets, biopores, biochannels, biovugs

Not mentioned in Table 10 is cratering due to artillery, an activity that is non-biologic, although tied to the humans. *Bombturbation*, or the cratering of the surface by explosive muntions, is a physical pedoturbative process that is capable of rendering drastic changes to a soilscape. When a soil surface is subjected to bombturbation, large parts of the surface impacted by such actions are exhumed to the point where the unaltered underlying parent material is now frequently exposed and subject to pedogenic processes. Here is where war differs from other forms of pedoturbation in regard to its magnitude and extent. Since tree-throw topography closely resembles cratering, I will use it as an example as a comparison with cratering due to artillery. Following a massive windstorm, a forest may be largely disturbed by tree uprooting, thus creating a pit and mount topography associated with treethrow pedoturbation. However, unlike the actions of artillery, the wind event that created the disturbance likely did not uproot 100% of the trees in the forest nor does it create craters where trees did not exist. Even if the winds associated with such a storm would uproot a large percentage of trees in an area, the area covered does not even come close to the area disturbed by artillery along the western front alone in WWI. In addition, when tree throw occurs a pit is created where the tree roots were and the ensuing mound is the tree roots and soil that were pushed up (Schaetzl 1990). When cratering occurs due to artillery, there is no mound associated with the tree-throw pit. The soil that formally occupied the crater is ejected outwards and thinly veils the soil surface in a given radius depending on the size of the munition surrounding the crater.

The cratering of a landscape associated with the actions of war are also capable of disturbing the soil to much deeper depths than other forms of pedoturbation. Keeping with tree-throw as an example, the depth of a tree-throw pit is often limited to the depth of bedrock or of some other layer that impedes root penetration such as a fragipan or perched water table (Schaetzl, Burns et al. 1990). When cratering is caused by light to medium artillery, the disturbance is limited to depth to bedrock. However, when larger artillery rounds are implemented, the disturbance often penetrates deep into the bedrock. In addition, when an area is heavily saturated with artillery craters, the disturbance penetrates deep into what was once solid bedrock, often to depths exceeding 10 meters as is the case in the vicinity of the Thiaumont Platform and battlefield forts, where the heaviest fighting occurred (Montagne, 2003; Figure 12).

In conclusion, although the cratering on the Verdun battlefield may at times resemble pit and mound topography associated with tree throw processes, or the landscape may resemble a mima-mound like surface associated with the activities of rodents, the magnitude and area of disturbance associated with bombturbation is incomparably larger in both cases. The implications of widespread bombturbation, although not yet fully understood, include drastic changes in the way a soilscape evolves after being subjected to such a disturbance.

Divergence in soilscape evolution

The term '*Butterfly Effect*' refers to a changing course of events due to some past occurrence. The term originates from a short story in Ray Bradbury's *Illustrated Man* (Bradbury 1967). In that story, a hunter goes back in time to hunt a *Tyrannosaurus Rex* dinosaur. The hunter deviated from a strictly intended path and ended up stepping on a small butterfly in the process. The hunter did not know he did this until the group returned back to present time, only to find out that humans and life as we know it were completely altered by this one seemingly small and insignificant event. Thus, the term *butterfly effect* is used to indicate that, over time, past actions can set events on a completely different evolutionary path. This concept can also be applied to principles of landscape evolution following disturbance, such as the disturbance to the Verdun battlefield (Phillips 1999, 2001).

Prior to WWI, the Verdun landscape consisted of agricultural valleys and densely covered forested ridges. The sedimentary bedrock and the regolith above it contained a variety of soils, with most of the soils being extremely thin due to the nature of the limestone bedrock. Generally, soils were thickest in the valleys, thinnest on the ridge slopes, and of varying composition and thickness on the ridge tops. In many locations along the bottoms of ridge slopes, villages were set up to take advantage of the many artesian wells in the area (Holstein 2002). The artesian springs resulted from water percolating through the porous limestone bedrock, only to become perched on a layer of clayey limestone, forcing the water to flow laterally until it came in contact with the ridge bottom (Montagne 2003).

The explosions associated with artillery shells of WWI have significantly altered the surface of the Verdun battlefield. Even 88 years after this initial disturbance, soil and landscape development have diverged along an altered path of landscape evolution –the butterfly effect of war. Although the activities surrounding soils and their development such as OM accumulation, leaching, and weathering occurred before WWI, they now act on the soil in different ways and in vastly different patterns, influenced by the highly altered microtopography. Even the human influence has been largely reduced. Agricultural villages that once inundated the area have all but disappeared due to the millions of craters and unexploded munitions beneath the surface. What was agricultural land is now covered with forest. In this regard, one could say that the disturbance has, in one way, allowed the landscape to truly revert back to its 'natural' state. While others have studied anthropogenic pedogenesis (Beyer et al 2001; Lebebdeva et al 1995; Roberts 1988), that is the human impact on soil development, the reversion of this formally agricultural landscape back into forest is a topic that calls for further attention and study in the future.

Besides regressive anthropogenic landscape evolution however, the landscape has evolved in other ways. Instead of smooth slopes that foster surface runoff, now the ridge slopes are pocked with craters that range in size from several meters across and 1-2 meters deep to craters that are 15 meters in diameter with depths exceeding 10 meters. The change to the surface micro and meso topography has had major effects on surface water flow lines and groundwater infiltration, not to mention soil development rates (Figure 65). Soil development is now *enhanced* along the ridge slope (in preferred sites - crater bottoms) due to the increased infiltration of water and organic matter contributions (Runge 1973). However, in locations where large hummocks divide the craters, the hummocks likely act in the same manner as tree throw mounds, shedding water and are experiencing only minimal soil development (Scheatzl 1990). In some locations that contain geologic conditions leading to perched water tables, 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. Situations like this not only impede soil development, but they also prevent forest vegetation from taking root since the trees are deprived of oxygen under such conditions.

Disturbance magnitude varies across the Verdun battlefield, ranging from severe (where the surface has been completely altered) to light, where only a few scattered craters dent the surface (Table 1). As discussed within the literature review in Chapter 2, the manner in which a landscape evolves following disturbance greatly depends on the magnitude of disturbance and the overall *stability* and *resilience* of that particular landscape. Landscape stability refers to the overall ability of a landscape to absorb any type of disturbance without becoming significantly altered while landscape resilience refers to the ability of a landscape to revert back to its original state following disturbance.

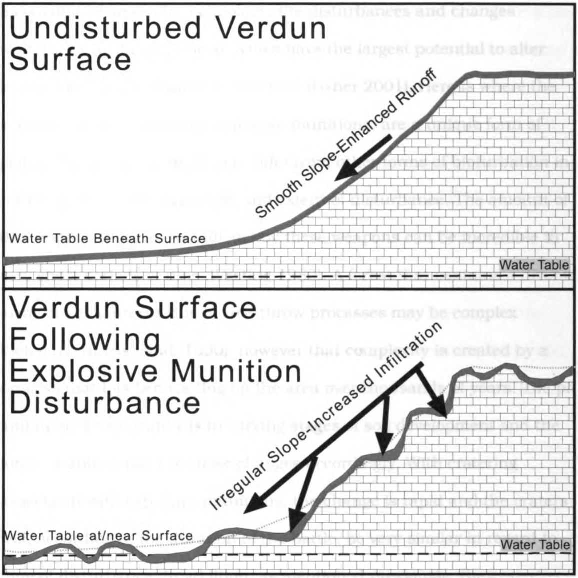


Figure 65. Generalized diagram of divergence in soil developmental pathways on the Verdun battlefield surface prior to and following disturbance by explosive munitions.

The magnitude and type of disturbance also determines the resilience and stability of any particular landscape. Landscapes are constantly subjected to varying forms of disturbance, whether they are anthropogenic or natural (Bazzaz 1983; Brunsden 2001. With all of the increasing advances in technology, the disturbances and changes wrought by anthropogenic activities have the largest potential to alter landscapes and landscape appearance (Usher 2001). Here is where the actions of war, in this case explosive munitions, are a unique form of pedoturbative disturbance that differ from other forms of bioturbation in regard to the sheer magnitude and extent of disturbance. The amount of disturbance that can be inflicted by these weapons can be incredible in very short periods of time (Westing 1980). A forest that contains a diverse array of soil patterns due to tree-throw processes may be complex (Schaetzl, Burns, et al. 1990), however that complexity is created by a process that has been acting on the area over thousands of years. The pit and mound topography is in varying stages of soil development and the forest is able to react to these changes accordingly. With cratering associated with explosive munitions, the change is rapid and the craters will, according to the duration of the battle, be very similar in regard to time of disturbance. In addition, as mentioned previously, the cratering is not limited to where trees exist and is capable of 100% disturbance of an area as seen by the surveys performed on the Thiaumont Platform (Figures 49, 50, 51).

Landscape recovery following large magnitude disturbances, such as war, is often measured using solely bio-ecologic factors – that is measures of vegetative growth. In the case of Verdun, the landscape may have revegetated quickly, but is far from full recovery, and nor has its recovery been uniform. While a thick mantle of vegetation now covers the battlefield, the surface is inundated with millions of small craters, many of which contain standing water. The millions of crater depressions have implications for surface hydrology, water table characteristics, and soil development rates. Bio-ecologic factors may, therefore provide only a partial picture of landscape recovery. Disturbances to soils and landforms take much longer to heal; it is important to use data from them in addition to vegetation as surrogates of landscape recovery. Examining soil development rates and the amount of cratering on the Verdun battlefield provide a better assessment of the true resilience and stability of this landscape, in those disturbed areas upon the battlefield, the landscape is far from 'recovering' back to its original state.

Chapter 6
Conclusions

A great deal of geographic literature has focused on the ways in which the physical environment has altered the outcome of military campaigns (Doyle and Bennett 2002; Demorlaine 1919; Guth 1998; Kiersch and Underwood 1998; Winters et al. 1998). However, very little research has focused on the impacts of war upon the environment. In the small body of research concerned the impact of war, the focus is on the immediate effects and relies on bio-ecologic factors to determine the magnitude and extent. In this research I have forged a new avenue of study within the realm of geomorphology by examining the impact of warfare upon the environment with the use of geomorphic and soil parameters.

The objectives of this Ph.D. research project were to examine, by using data from soils and geomorphology, (1) the magnitude and variability of disturbance due to explosive munitions across the WWI battlefield of Verdun, France, and (2) the degree of landscape recovery that has occurred in the 88 years since the disturbance. The Verdun battlefield was chosen over other battlefields to assess post-war disturbance primarily because (1) it was an area of extreme disturbance due to the large numbers of and prolonged use of artillery, (2) the time of disturbance was known to within a year, and (3) the battle occurred within a fairly confined area.

Disturbance magnitude at the Verdun battlefield was based upon the degree and extent of cratering in a given area, while recovery was based upon criteria indicative of soil development. The degree of soil development was largely based upon principles of the Runge (1973) energy model. Indicators of development included: horizon development, relative degree of translocation of clay, leaching (removal) of mobile (eg. Ca, Mg, K) vs. immobile (Zr and Ti) elements, pH, and organic carbon accumulation. Most studies of landscape disturbance and recovery have traditionally relied solely upon bio-ecologic factors as an indicator of landscape recovery. This study examined the changes wrought upon a catastrophically disturbed landscape through a survey of microtopography and soil development. While a survey of vegetation would lead to erroneous assumptions of landscape recovery, the use of soils and geomorphic data presents a much clearer picture of the actual changes this landscape has undergone due to the disturbance. This work also illustrates that when landscapes are disturbed to this magnitude and extent, they never truly recover and only vary in regard to how much they differ from the original.

The spatial character and variations in the magnitude of disturbance at the five disturbance study was attributed to the following four variables: (1) location of armies in relation to the front lines, (2) degree of stagnation in regard to movement of armies, (3) topographic location of armies, and (4) geologic characteristics of the site. Magnitudes of disturbance were mostly attributable to the first two variables mentioned above.

Signs of soil development within craters were visibly apparent by the formation of O and A horizons above a C horizon that, prior to disturbance, was unweathered bedrock. In several locations, such as crater three at the Red Zone site, a weakly developed B horizon was observed in the crater bottoms. In addition to visible signs of soil development in craters, these soils were markedly different than those undisturbed soils adjacent to the craters. Soils within craters at each of the three study sites contained substantially darker and thicker A horizons than those undisturbed soils adjacent to the crater bodies. The A horizons were generally thickest at the crater bottom and thinned out progressing towards the crater rim. Organic horizons followed the same pattern as A horizons at the Red Zone site, but were generally absent at the Bois de Thill and Etraye sites. The loss on ignition (LOI) procedure clearly demonstrated that organic carbon amounts generally were highest within the craters and tapered off moving towards the crater rim.

Soil development within craters was also made apparent by the data generated in the XRF and pH analysis. Elemental ratios, designated to signify the degree of weathering in the soil column, displayed trends that showed weathering (and thus soil formation) within the crater disturbances. The elemental ratios also indicated that, while weathering was occurring within the craters, the undisturbed adjacent soils were more weathered than the recently disturbed material exposed in the crater depressions. The depth plot trends supported the data generated from XRF analysis by also displaying lower pH values at the top of the profile that gradually increased with depth. Both the XRF and pH depth plot trends show the weathering of the soil from the top of the profile downward.

While other bodies of research have examined soil development using these parameters on other previously disturbed surfaces, this study is unique in that it examines the development of a soil 88 years after the initial disturbance took place, unlike other bodies of research that examined soil development after several hundred, sometimes thousands of years. The Verdun battlefield presented itself as a wonderful opportunity to examine short term disturbance due to the knowledge of when that disturbance took place to, in some cases, within month. In addition, the depth of the disturbance exposed previously unweathered bedrock, thus allowing for a true assessment of the degree of weathering that occurs in 88 years on a newly exposed surface.

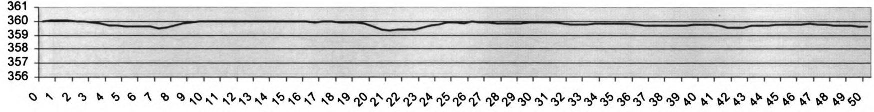
Despite the advantages of Verdun over other battlefields to conduct a study such as this, many battlefields around the world also need to be examined to assess the degree of disturbance and recovery within those areas. More research needs to be done in a variety of climates to determine how landscapes subjected to the disturbances of war, in this case explosive munitions, have recovered following those activities. The

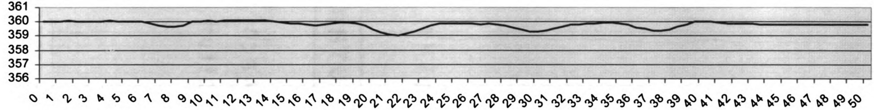
Vietnam landscape, the deserts of the Middle East, and numerous islands in the Pacific (see earlier chapters) are just some of many battlefields around the world that hold promise as we expand this realm of military geography.

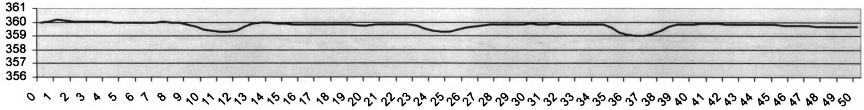
Why study the impact of war upon the environment? As we have seen, from the beginnings of warfare, the environment has suffered, both incidentally and intentionally. The actions of war extend far beyond the various types of disturbances occurring at military training facilities around the world; war is global, far in scope, and its effects often recognize no political boundaries. Military geography needs to extend its traditional boundaries of examining the environmental influences and begin to explore the alternate scenario – the results of battle *upon* the environment. This sort of research has the promise to open many avenues of research within the academic realm. With these sorts of outside influences, military geography can expand into realms that not only may promote the advancement of scientific theories concerning landscape recovery following disturbance (such as military training grounds), but also promises to promote the view of military geography held by those outside the sub-discipline.

APPENDICES

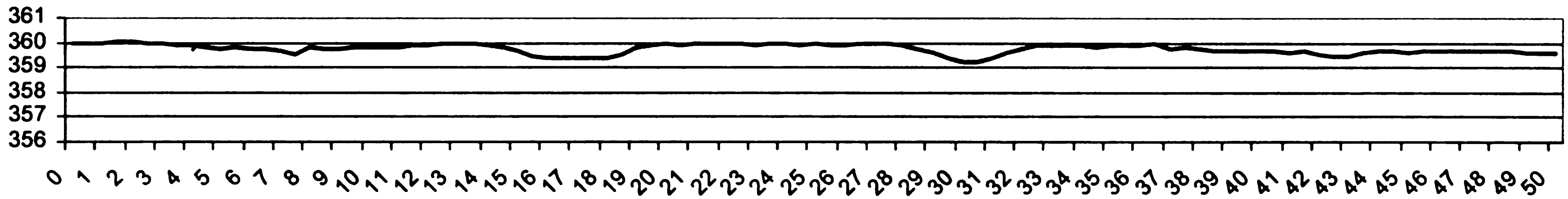
Appendix A1: Microtopographic Survey Treansect, Etraye Plot 1

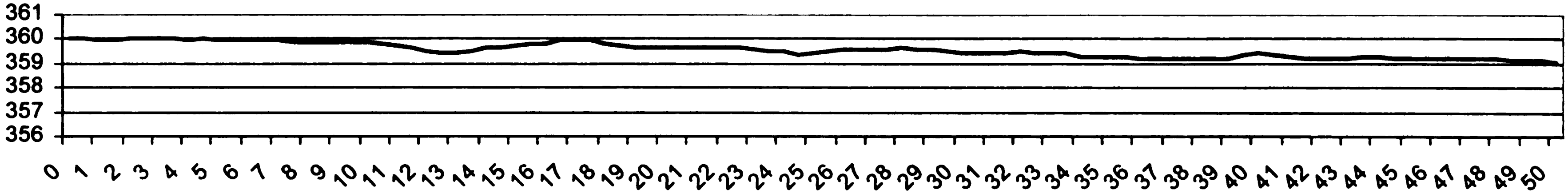


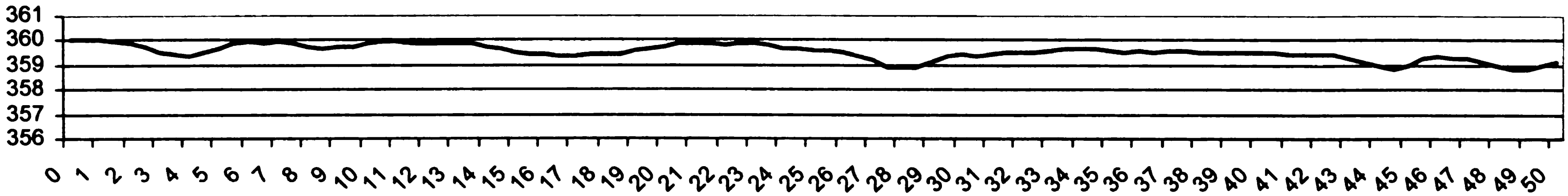




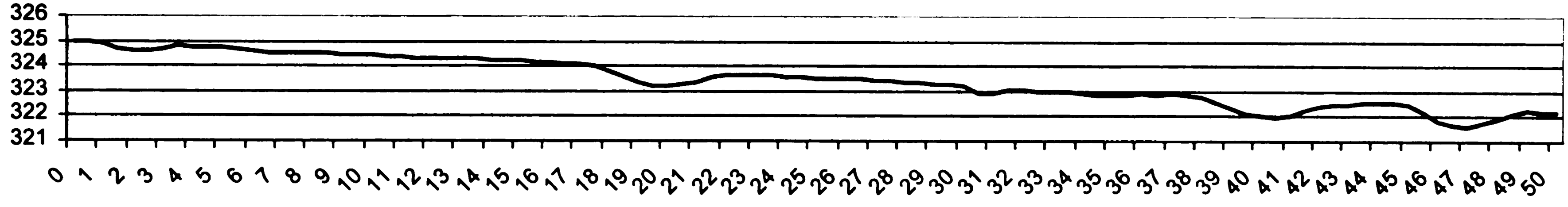
Appendix A2: Microtopographic Survey Treansect, Etraye Plot 2

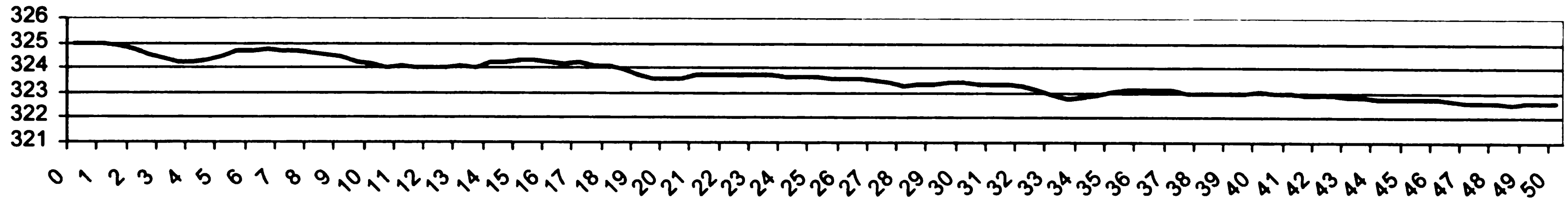


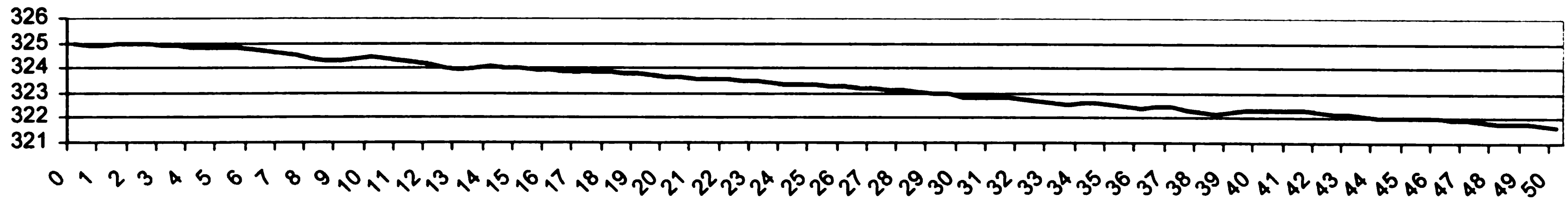




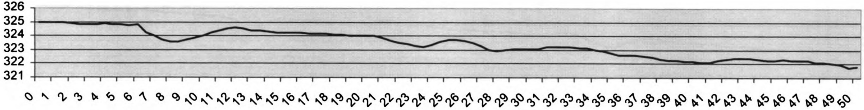
Appendix A3: Microtopographic Survey Treansect, Red Zone North, Plot 1

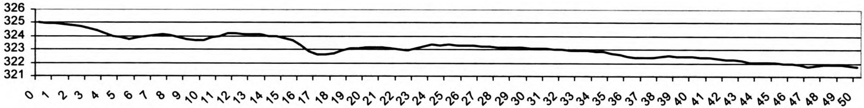


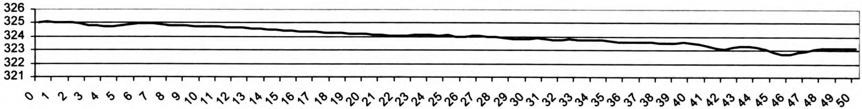




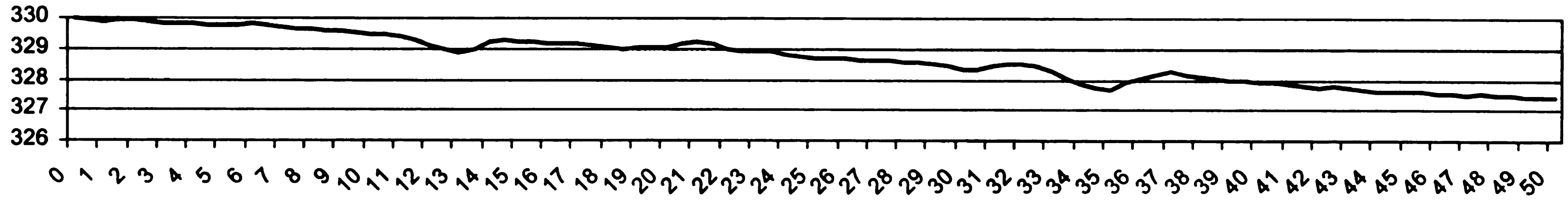
Appendix A4: Microtopographic Survey Treansect, Red Zone North, Plot 2

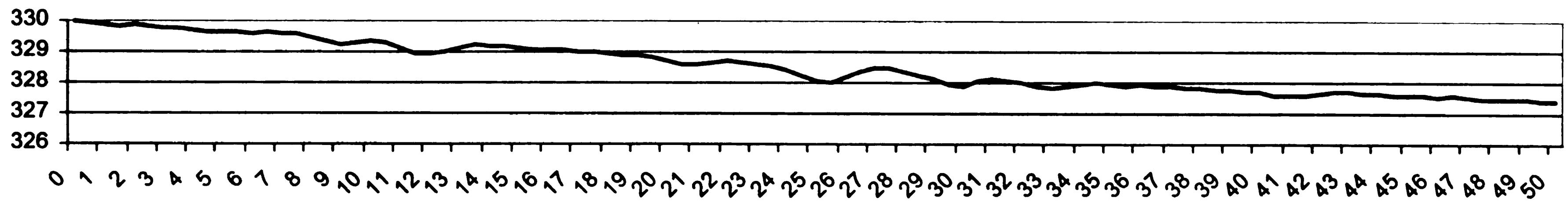


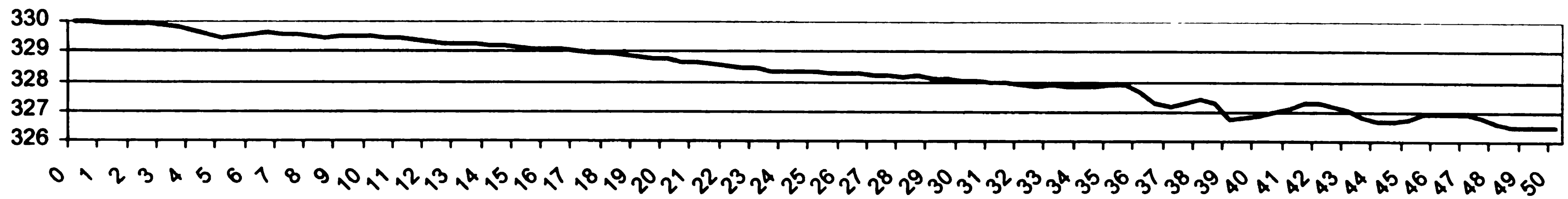




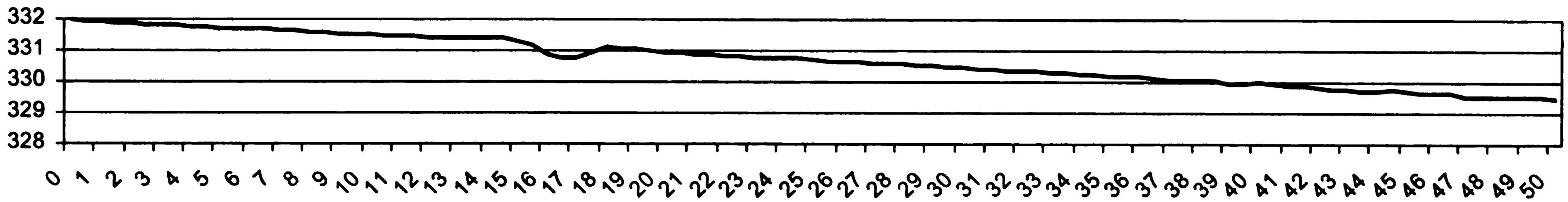
Appendix A5: Microtopographic Survey Treansect, Red Zone South, Plot 1

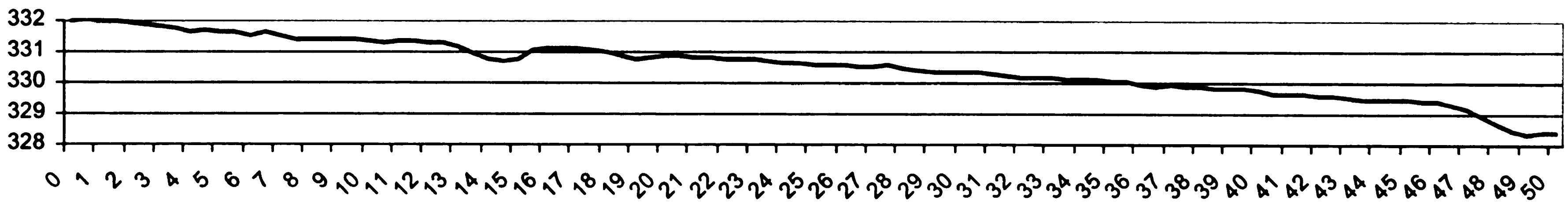


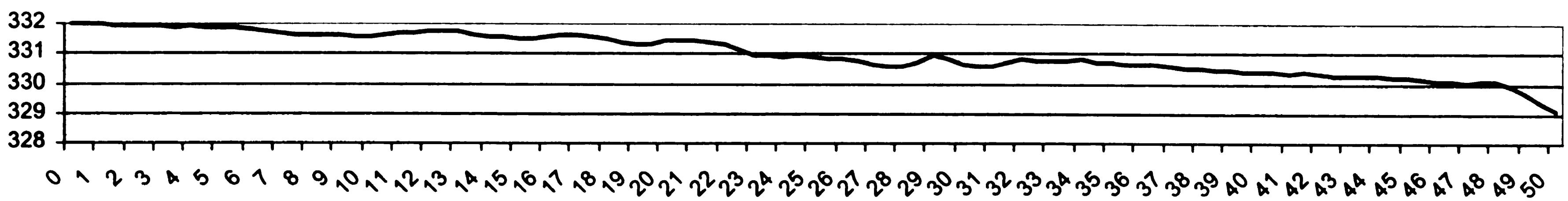




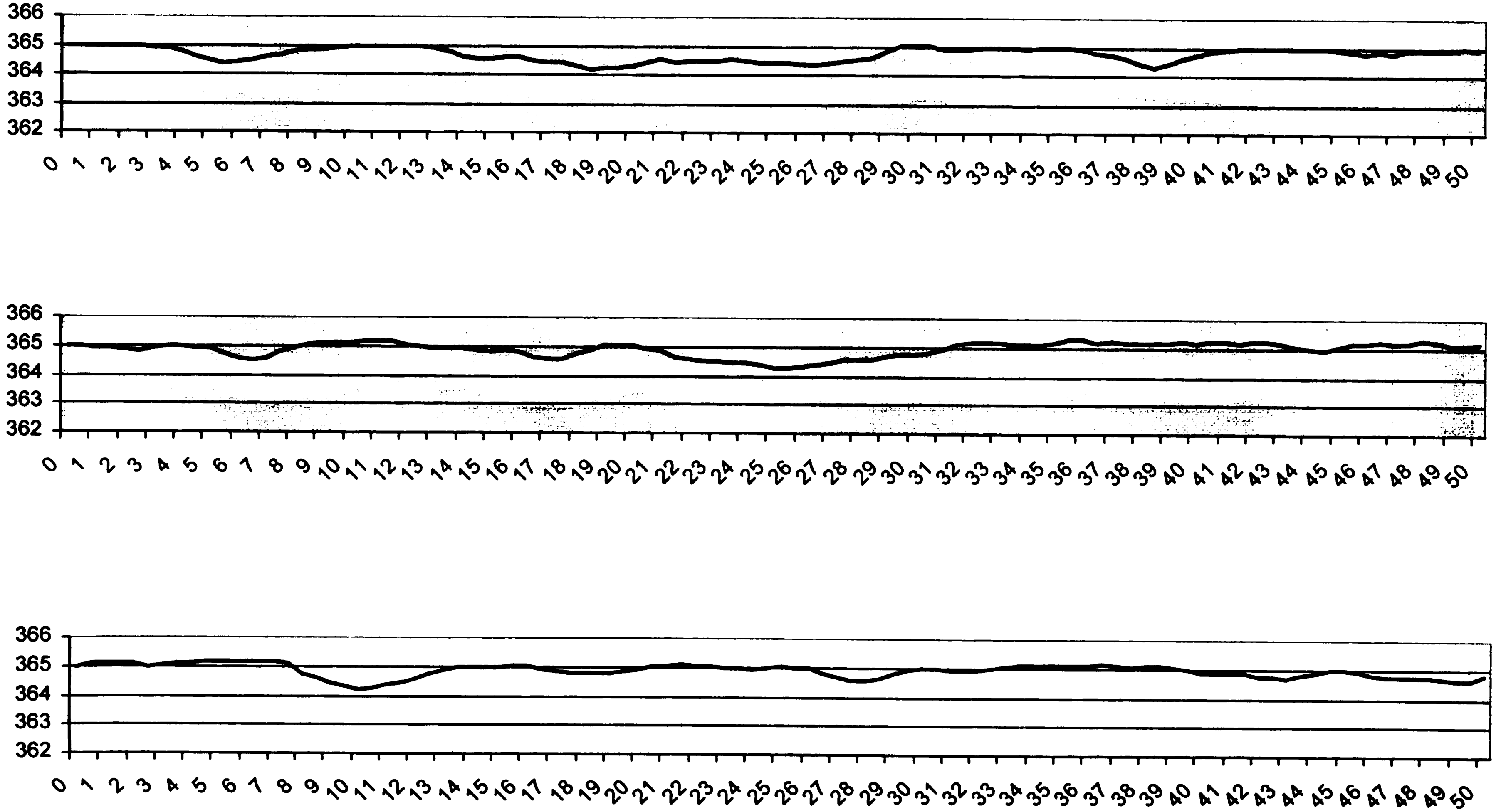
Appendix A6: Microtopographic Survey Treansect, Red Zone South, Plot 2



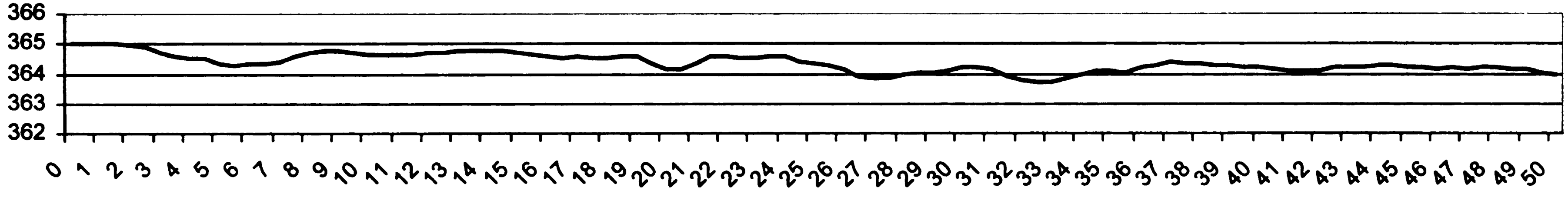


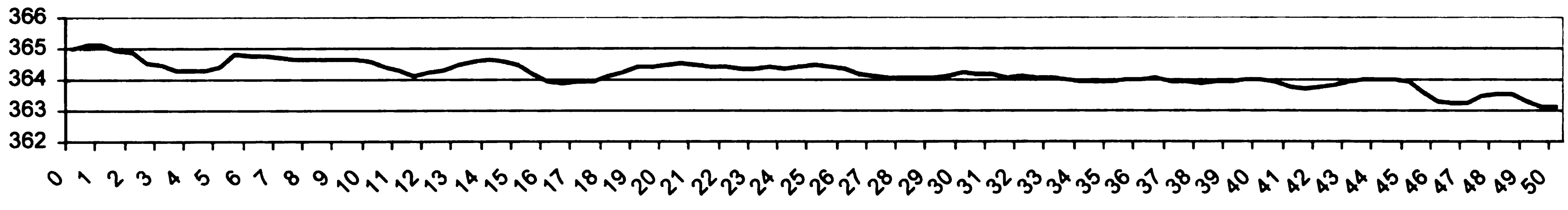


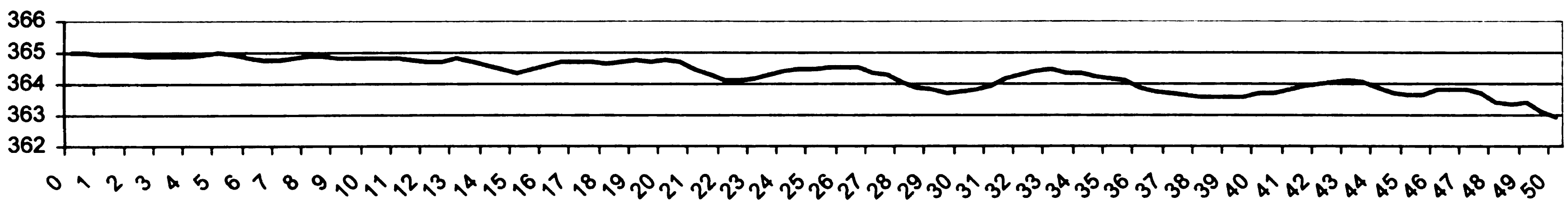
Appendix A7: Microtopographic Survey Treansect, Hoseland, Plot 1



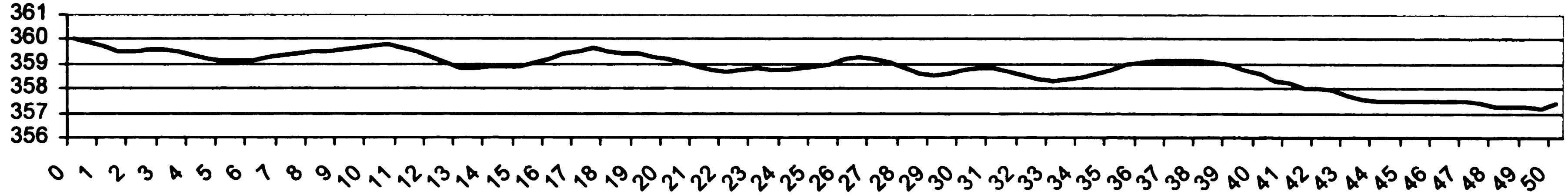
Appendix A8: Microtopographic Survey Treansect, Hoseland, Plot 2

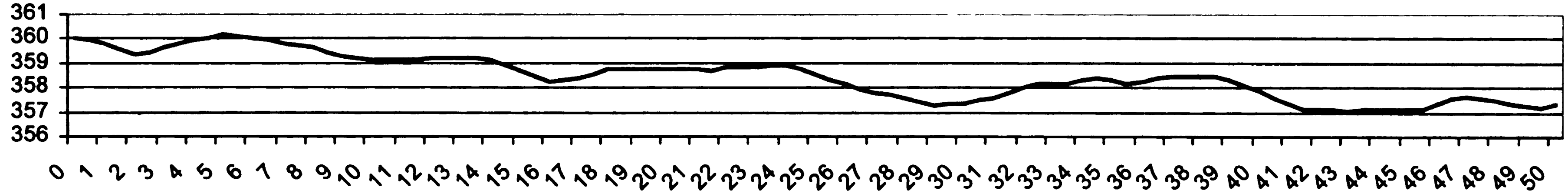


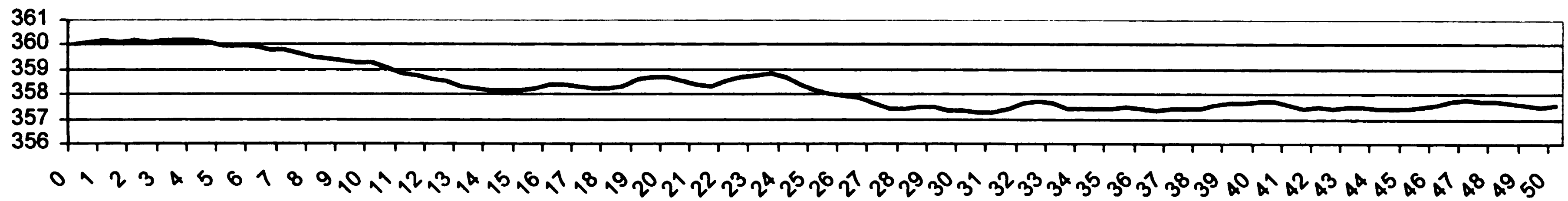




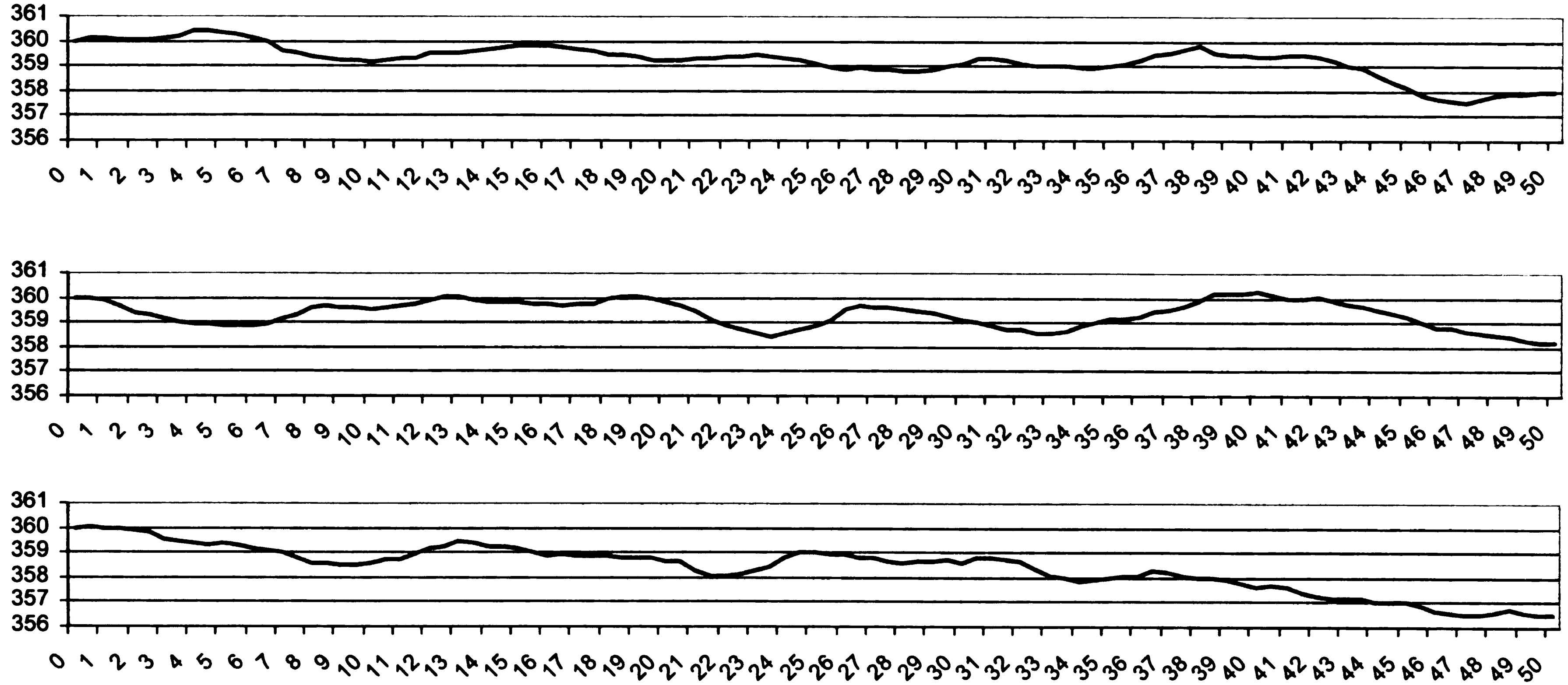
Appendix A9: Microtopographic Survey Treansect, Thiaumont Platform, Plot 1







Appendix A10: Microtopographic Survey Treansect, Thiaumont Platform, Plot 2



Appendix B: Morphological and physical data for soils and sediments

Site and Pedon	Horizon	Depth	Munsell Color (moist)	Structure	Consistence (moist)	Bdy	Coarse Frags (%)
Red Zone 1							
Crater Bottom	Oi	0-12	10 YR 3/2	------	----	AS	none
	A1	12-22	7.5 YR 3/2	2 f gr	FI	CS	5 fine gravel
	A2	22-29	10 YR 4/2	2 f gr	FI	CS	5 fine gravel
	Cr1	29-41	7.5 YR 8/2	1 m sbk	VFR	CS	50 cobbles 30 coarse gravel
	Cr2	41+	7.5 YR 8/2	1 m sbk	VFR	---	50 cobbles 30 coarse gravel
Crater Side	Oi	0-5	10 YR 3/2	----	----	AS	none
	A1	5-12	10 YR 4/3	2 f gr	FR	CS	5 fine gravel
	A2	12-23	10 YR 5/3	2 f gr	FR	AS	5 fine gravel
	Cr1	23-51	10 YR 7/4	1 m sbk	VFR	GS	40 cobbles 20 coarse gravel
	Cr2	51+	10 YR 8/4	1 m sbk	VFR	---	50 cobbles 30 coarse gravel
Undisturbed	Oi	0-3	10 YR 3/2	----	----	AS	none
	A	3-29	10 YR 4/3	3 m gr	VFI	CS	none
	Bw1	29-44	7.5 YR 4/4	3 m sbk	VFI	CS	25 med gravel
	Bw2	44-58	7.5 YR 4/4	3 f sbk	FI	CS	25 med gravel
	Cr	58-67	10 YR 7/4	1 f abk	VFR	D W	60 coarse gravel
	R	67+	10 YR 8/4	----	----	----	----
Red Zone 2							
Crater Bottom	Oi	0-8	10 YR 3/2	---	---	CS	none
	A	8-17	10 YR 4/3	1 m/f gr	VFI	CS	25 coarse gravel
	A/C	17-33	10 YR 4/2	1 m/f sbk	VFI	G W	35 coarse gravel
	Cr	33+	10 YR 7/3	1 vf sbk	VFI	---	50 cobbles 30 coarse gravel
Crater Side	Oi	0-8	10 YR 3/2	---	---	CS	none
	A	8-24	10 YR 4/3	2 m/f gr	FI	GS	35 coarse gravel
	Cr	24+	10 YR 7/3	1 vf sbk	VFR	---	50 cobbles 30 coarse gravel
Undisturbed	Oi	0-4	10 YR 3/2	---		AS	none
	A	4-17	10 YR 3/2	3 m gr	VFI	CS	10 med gravel
	Bw	17-29	7.5 YR 3/4	3 f gr/sbk	FR	CW	20 cobbles 10 coarse gravel
	Cr1	29-55	5 YR 3/4 10 YR 8/2	1 vf abk	VFR	G W	50 cobbles 25 coarse gravel
	Cr2	55+	10 YR 6/4	1 vf abk	L	---	70 cobbles 20 coarse gravel
Red Zone 2							
Crater Bottom	Oi	0-15	10 YR 2/2	---	---	CS	none
	A	15-32	10 YR 3/2	2 f gr	FR	CS	25 med gravel
	Bw	32-56	10 YR 5/4	2 f sbk	FI	CS	30 med gravel
	Cr1	56+	2.5 YR 7/2	1 f/vf sbk	VFR	---	50 cobbles 30 coarse gravel

Appendix B: (con't)

Crater Side	Oi	0-9	10 YR 2/2	---	---	CS	none
	A	9-25	10 YR 3/2	2 f gr	FR	CW	30 coarse gravel
	Bw	25-47	10 YR 5/4	2 f gr/sbk	FI	CW	25 coarse gravel 25 cobbles
	Cr	47+	2.5 YR 7/2	1 f sbk	VFR	---	60 cobbles 20 coarse gravel
Undisturbed	A	0-11	10 YR 3/3	3 f/m gr	FR	G W	20 fine gravel
	Bw1	11-27	5 YR 4/6	3 f/m gr/sbk	FI	G W	50 med gravel
	Bw2	27-38	5 YR 4/6	1 f sbk	FR	G W	50 coarse gravel 30 cobbles
	Cr	38+	2.5 Y 7/2	1 f sbk	VFR	---	50 cobbles 30 coarse gravel
Bois de Thill 1							
Crater Bottom	A1	0-9	10YR 2/1	2 vf/f gr	FR	CS	none
	A2	9-23	10 YR 2/1	3 m gr	FI	AS	none
	Cg1	23-60	5 YR 4/6 5 YR 5/2	2 m/c sbk	VFI	G W	none
	Cg2	60+	5 YR 4/6 5 YR 5/2	2 m/c sbk	VFI	---	none
Crater Side	A	0-19	10 YR 2/1	2 f/m gr	FI	CS	none
	Cg1	19-52	5 YR 4/6 5 YR 5/2	2 m/c sbk	VFI	GS	none
	Cg2	52+	5 YR 4/6 5 YR 5/2	2 m/c sbk	VFI	---	none
Undisturbed	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	G W	none
	Cg2	91+	5 YR 4/6 5 YR 4/6	2 m/c sbk	VFI	---	10 med gravel
Bois de Thill 2							
Crater Bottom	A	0-19	5 YR 2.5/1	2 vf/f gr	FR	CS	none
	Cg1	19-34	5 YR 4/6 5 YR 5/2	2 m/c sbk	VFI	G W	none
	Cg2	34+	2.5 Y 5/2	2 m/c sbk	VFI	---	5 coarse gravel
Crater Side	A	0-23	7.5 YR 3/2	2 f/m gr/sbk	VFI	GS	none
	Cg1	23-44	5 YR 4/6 5 YR 5/2	2 m/c sbk	VFI	G W	none
	Cg2	44+	5 YR 4/6 5 YR 4/2	2 m/c sbk	VFI	---	5 med gravel
Undisturbed	A	0-4	7.5 YR 3/2	2 vf/f gr	FR	AS	none
	AB	4-20	7.5 YR 3/2 10 YR ¾	2 m/c gr/sbk	FI	GS	none
	Bg	20-53	10 YR 5/4	2 m/c sbk	VFI	D W	none
	Cg	53+	5 YR 4/2 5 YR 4/6	2 m/c sbk	VFI	---	none

Appendix B: (con't)

Bois de Thill 3							
Crater Bottom	A	0-4	7.5 YR 3/2	2 vf/f gr	FR	AS	none
	AB	4-20	7.5 YR 3/2 10 YR ¾	2 m/c gr/sbk	FI	GS	none
	Bg	20-53	10 YR 5/4	2 m/c sbk	VFI	D W	none
	Cg	53+	5 YR 4/2 5/YR 4/6	2 m/c sbk	VFI	---	none
Crater Side	A	0-18	5 YR 2.5/1	3 f gr	FR	AS	none
	Cg1	18-28	2.5 Y 7/2 2.5 7/8	2 m/c sbk	VFI	CS	15 fine gravel
	Cg2	28-69	2.5 Y 6/2 7.5 YR 6/6	2 m/c sbk	VFI	G W	15 fine gravel
	Cg3	69+	2.5 Y 6/2 7.5 YR 6/6	2 m/c sbk	VFI	---	20 fine gravel
Undisturbed	A	0-29	7.5 YR 3/2	2 f/m gr	VFI	GS	none
	A/Bg	29-46	7.5 YR 3/2 2.5 Y 6/2 7.5 YR 5/6	3 m/c sbk/gr	VFI	G W	none
	Cg1	46-80	2.5 Y 6/2	2 m/c sbk	VFI	D W	15 fine gravel
	Cg2	80+	2.5 Y 6/2	2 m/c sbk	VFI	---	15 fine gravel
Etraye 1							
Crater Bottom	Oi	0-4	10 YR 2/1	---	---	AS	none
	A1	4-13	10 YR 3/1	2 f/vf gr	FI	CS	20 med gravel
	A2	13-29	10 YR 3/1	2 f/vf gr	FI	CW	30 med gravel
	A/Cr	30+	10 YR 7/8	1 f/vf gr	FI	---	70 cobbles 20 med gravel
Crater Side	A	0-12	10 YR 2/1	2 f/m gr			60 med gravel
	Cr1	12-29	10 YR 3/1	1 f sbk			60 med gravel
	Cr2	29-51	10 YR 3/1	1 vf/f sbk			60 med gravel
	R	51+	10 YR 7/8	---	---	---	Solid Bedrock
Undisturbed	A1	0-19	10 YR 3/1	3 m/c gr	VFI	CI	25 coarse gravel
	A2	19-36	10 YR 4/3	2 m gr	VFI	GI	60 coarse gravel
	Cr1	36-53	10 YR 6/6	2 m sbk	FI	G W	60 coarse gravel
	Cr2	53-64	10 YR 6/6	2 m sbk	FI	G W	80 coarse gravel
	R	64+	10 YR 7/8	---	---	---	Solid Bedrock
Etraye 2							
Crater Bottom	A	0-28	10 YR 3/1	2 f/m gr	FR	GI	30 coarse gravel
	Cr	28-43	10 YR 6/6	2 m sbk	VFI	GI	60 coarse gravel
	R	43+	10 YR 7/8	---	---	---	---
Crater Side	A	0-11	10 YR 3/1	2 f/m gr	FR	GI	30 coarse gravel
	Cr	11-53	10 YR 6/6	2 m sbk	VFI	GI	60 coarse gravel
	R	53+	10 YR 7/8	---	---	---	---

Appendix B: (con't)

Undisturbed	A1	0-18	10 YR 3/1	3 f gr	FR	GS	10 coarse gravel 10 cobbles
	A2	18-39	10 YR 5/6	3 f/m gr/sbk	VFI	GI	40 gravel 20 cobbles
	Cr1	39-71	10 YR 5/6	2 m/c sbk	VFI	GI	40 gravel 20 cobbles
	Cr2	71+	10 YR 5/6	2 m/c sbk	VFI	---	60 cobbles 20 gravel
Etraye 3							
Crater Bottom	Oi	0-5	7.5 YR 3/0	---	---	CS	none
	A	5-22	2.5 Y 2/0	1 f gr	VFI	A W	20 coarse gravel
	Cr	22+	10 YR 5/6	1 m/c sbk	VFI	---	60 cobbles
Crater Side	A	0-11	10 YR 3/1	3 m/c gr	VFI	CI	30 coarse gravel
	Cr1	11-45	10 YR 5/6	2 m/c sbk	VFI	AI	50 coarse gravel
	Cr2	43+	10 YR 5/6	2 m/c sbk	VFI	---	60 cobbles 20 coarse gravel
Undisturbed	A	0-6	10 YR 3/2	3 m gr	SR	CS	20 med gravel
	ABw	6-31	10 YR 4/4	3 m/c gr/sbk	SR	CW	30 med gravel
	Cr1	31-52	10 YR 5/6	2 m/c sbk	VFI	G W	60 cobbles 20 coarse gravel
	Cr2	52-67	10 YR 5/6	1 m sbk	VFI	G W	60 cobbles 20 coarse gravel
	Cr3	67+	10 YR 5/6	1 f sbk	FI	---	60 cobbles 30 coarse gravel

Appendix C: Textural data for soils and sediments

Site and Pedon	Depth	Sand	Silt	Clay	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	USDA Texture Class
	(cm)	--(%)--								
Red Zone 1										
Crater Bottom	10	---	---	---	---	---		---	---	---
	20	40.4	32.2	27.4	8.1	19.9	6.3	3.0	3.1	clay loam
	30	39.8	26.8	26.8	6.9	16.2	7.6	4.1	5.0	loam
	50	37.9	24.3	24.3	16.2	11.0	5.6	2.9	2.3	loam
Crater Side	10	49.5	22.1	22.1	10.3	24.2	8.5	3.3	3.2	loam
	20	47.6	22.8	22.8	10.9	19.9	8.3	4.3	4.2	loam
	30	54.7	20.2	20.2	9.4	24.3	11.2	5.5	4.3	sandy clay loam
	50	46.0	21.4	21.4	7.1	11.9	8.1	6.6	12.3	loam
Undisturbed	10	5.4	28.9	28.9	0.4	0.4	0.4	0.7	3.6	silty clay loam
	20	6.8	27.9	27.9	0.0	0.1	0.4	0.9	5.5	silty clay loam
	30	7.0	37.3	37.3	1.9	1.6	0.9	0.6	1.8	silty clay loam
	50	36.7	33.4	33.4	13.5	14.7	4.2	2.0	2.3	clay loam
Red Zone 2										
Crater Bottom	10	36.4	30.9	32.7	6.7	15.2	6.5	3.8	4.1	clay loam
	20	37.9	34.5	27.6	10.8	16.2	5.3	2.8	2.9	clay loam
	30	50.2	27.4	22.4	15.5	21.5	6.4	3.6	3.2	sandy clay loam
	50	66.8	8.9	24.3	10.7	33.2	12.2	6.3	4.4	sandy clay loam
Crater Side	10	36.5	31.8	31.7	7.2	16.1	6.5	3.4	3.3	clay loam
	20	54.2	20.7	25.1	15.1	23.9	8.0	4.1	3.2	sandy clay loam
	30	59.5	19.0	21.5	13.0	27.1	10.1	5.3	4.0	sandy clay loam
	50	69.5	14.7	15.9	19.4	35.9	8.2	3.3	2.6	sandy loam
Undisturbed	10	45.1	39.6	15.3	9.1	17.6	7.4	4.3	6.7	loam
	20	51.1	37.3	11.6	23.4	14.3	5.7	3.3	4.5	loam
	30	32.4	42.7	24.9	12.5	11.0	3.7	1.9	3.3	loam
	50	53.6	25.3	21.1	20.8	23.6	4.3	2.2	2.7	sandy clay loam

Appendix C (con't)

Red Zone 3										
Crater Bottom	10	---	---	---	---	---	---	---	---	---
	20	39.7	46.0	14.3	7.2	17.5	6.7	3.9	4.4	loam
	30	47.5	33.8	18.7	12.5	20.6	6.4	3.8	4.1	loam
	50	39.1	41.5	19.4	9.4	16.2	5.6	3.3	4.7	loam
Crater Side	10	---	---	---	---	---	---	---	---	---
	20	32.4	43.8	23.8	10.9	12.2	4.3	2.3	2.8	loam
	30	46.0	32.7	21.2	15.5	19.1	5.7	2.7	3.1	loam
	50	48.0	31.2	20.8	8.8	11.6	8.1	7.1	12.5	loam
Undisturbed	10	2.9	56.3	40.9	0.0	0.5	0.4	0.5	1.6	silty clay
	20	27.9	54.9	17.2	7.3	7.3	7.3	3.8	2.1	silt loam
	30	35.7	51.9	12.4	10.3	11.8	5.0	3.4	5.1	silt loam
	50	50.0	33.0	17.0	11.8	21.0	8.7	4.5	4.1	loam
Bois de Thill 1										
Crater Bottom	10	26.2	33.2	40.6	2.1	5.2	2.1	2.7	14.2	clay
	20	17.1	33.5	49.4	0.8	1.0	1.0	0.9	13.3	clay
	30	21.5	25.6	52.9	0.3	0.5	0.5	1.0	19.3	clay
	50	21.7	25.7	52.6	0.2	0.3	0.2	0.7	20.4	clay
Crater Side	10	22.8	24.2	53.0	0.5	0.4	0.6	0.8	20.5	clay
	20	22.0	23.8	54.1	0.2	0.2	0.3	0.7	20.7	clay
	30	23.6	24.3	52.1	0.1	0.3	0.2	0.6	22.4	clay
	50	24.0	29.0	47.0	1.1	1.8	1.3	1.9	18.0	clay
Undisturbed	10	26.4	31.0	42.6	0.9	1.1	1.0	1.3	22.2	clay
	20	23.8	30.0	46.1	1.1	0.8	0.7	0.9	20.2	clay
	30	19.0	29.1	51.9	0.6	0.8	0.6	0.7	16.4	clay
	50	19.7	25.2	55.1	0.3	0.3	0.4	0.7	18.1	clay
Bois de Thill 2										
Crater Bottom	10	15.5	29.2	55.4	0.4	0.5	0.4	0.6	13.5	clay
	20	19.2	25.7	55.1	0.4	0.7	0.5	0.6	16.9	clay
	30	20.3	25.4	54.3	0.6	0.8	0.6	0.7	17.6	clay
	50	29.0	24.0	47.1	1.4	1.7	1.3	2.0	22.5	clay
Crater Side	10	19.8	24.9	55.3	0.8	0.8	0.8	0.6	16.9	clay
	20	17.5	27.7	54.8	0.7	0.8	0.6	0.5	14.8	clay

Appendix C (con't)

	30	16.9	26.1	56.9	0.4	0.5	0.7	0.7	14.5	clay
	50	19.7	29.8	50.5	0.4	0.8	0.9	0.9	16.7	clay
Undisturbed	10	15.6	37.4	47.0	0.2	0.6	0.6	0.6	13.6	clay
	20	20.1	30.3	49.6	0.5	0.6	0.6	0.7	17.9	clay
	30	17.1	29.9	53.0	0.4	0.5	0.5	0.5	15.2	clay
	50	16.6	27.4	55.9	0.7	0.7	0.4	0.4	14.5	clay
Bois de Thill 3										
Crater Bottom	10	21.3	33.8	45.0	0.9	0.8	0.7	0.8	18.1	clay
	20	18.8	33.6	47.6	1.6	1.4	1.0	0.8	14.1	clay
	30	23.9	34.4	41.7	1.6	1.7	1.7	1.5	17.4	clay
	50	28.0	34.8	37.2	2.0	2.0	1.4	2.2	20.5	clay loam
Crater Side	10	22.9	40.4	36.7	0.9	1.0	1.6	1.5	18.0	clay loam
	20	24.3	36.9	38.8	1.6	1.4	0.9	2.0	18.5	clay loam
	30	19.4	30.1	50.5	0.4	0.1	0.2	0.5	18.3	clay
	50	23.8	25.9	50.2	0.1	0.1	0.1	0.4	23.2	clay
Undisturbed	10	24.6	34.1	41.3	0.8	0.9	1.0	1.3	20.6	clay
	20	24.4	35.3	40.3	0.7	0.8	0.7	0.9	21.3	clay
	30	21.0	31.3	47.8	0.8	0.7	0.6	0.7	18.1	clay
	50	52.4	20.6	26.9	8.1	6.9	4.4	6.1	26.9	sandy clay loam
Etraye 1										
Crater Bottom	10	25.1	44.8	30.0	7.8	6.0	3.2	2.1	6.2	clay loam
	20	24.0	38.8	37.3	7.4	5.7	3.4	2.2	5.3	clay loam
	30	34.1	32.7	33.2	13.0	7.4	3.7	2.5	7.5	clay loam
	50	39.4	14.5	46.1	22.4	8.1	3.9	1.8	3.2	clay
Crater Side	10	30.1	24.9	45.0	14.0	6.7	3.2	1.9	4.4	clay
	20	52.1	13.6	34.3	33.3	9.0	5.3	2.0	2.5	sandy clay loam
	30	56.7	10.5	32.8	27.4	13.3	10.0	3.4	2.5	sandy clay loam
	50	58.6	7.2	34.2	32.8	14.9	7.3	2.2	1.4	sandy clay loam
Undisturbed	10	15.5	47.0	37.5	15.5	0.0	0.0	0.0	0.0	silty clay loam
	20	19.0	49.7	31.3	0.3	1.4	3.1	3.2	11.2	silty clay loam
	30	17.4	48.9	33.7	0.5	1.7	2.4	1.8	11.1	silty clay loam
	50	43.7	13.8	42.5	21.5	9.8	6.4	2.8	3.1	clay

Appendix C (con't)

Etraye 2										
Crater Bottom	10	15.2	32.0	52.7	2.4	2.1	1.6	1.6	7.4	clay
	20	15.4	28.2	56.4	2.6	2.7	2.0	1.9	6.3	clay
	30	16.2	13.2	70.5	3.5	3.7	3.3	2.3	3.4	clay
	50	14.0	20.1	66.0	2.7	3.4	2.9	2.2	2.8	clay
Crater Side	10	11.6	29.3	59.2	0.3	0.2	0.3	0.6	10.2	clay
	20	10.8	28.0	61.2	0.2	0.6	0.8	0.9	8.3	clay
	30	13.9	34.7	51.4	1.1	2.1	2.8	1.9	5.9	clay
	50	11.6	14.5	73.9	1.8	2.4	2.5	1.9	3.0	clay
Undisturbed	10	13.4	34.0	52.6	0.7	1.3	1.2	1.4	8.8	clay
	20	11.3	31.2	57.5	0.1	0.6	0.9	1.1	8.6	clay
	30	12.8	39.8	47.4	0.4	1.0	1.4	1.2	8.8	clay
	50	5.2	18.5	76.3	0.2	0.6	0.4	0.6	3.4	clay
Etraye 3										
Crater Bottom	10	---	---	---	---	---	---	---	---	---
	20	14.1	37.0	48.9	4.5	3.5	2.0	1.3	2.8	clay
	30	6.5	22.2	71.2	1.1	1.2	1.2	1.2	1.9	clay
	50	14.0	19.7	66.3	3.1	3.5	2.6	2.1	2.7	clay
Crater Side	10	15.1	26.8	58.1	2.5	2.3	1.8	1.4	7.2	clay
	20	25.9	24.4	49.7	6.3	6.8	5.4	3.2	4.2	clay
	30	22.4	20.8	56.8	7.7	6.1	3.4	2.2	2.9	clay
	50	17.9	15.9	66.1	3.6	4.4	3.8	2.8	3.3	clay
Undisturbed	10	13.1	37.0	50.0	1.0	0.7	0.3	0.7	10.3	clay
	20	17.7	39.5	42.8	0.6	0.6	3.8	8.8	3.8	clay
	30	14.3	34.3	51.4	0.1	0.1	0.3	0.9	12.9	clay
	50	31.9	36.2	31.9	9.5	7.6	5.5	3.9	5.4	clay loam

Appendix D: Chemical data for soils and sediments

Site and Pedon	Depth	pH	Organic Carbon (L.O.I)	Weathering Indexes	
				(ti+zr)/ (ca+mg+k)	(ti+zr)/ (ca+mg+k+mn+na+p)
	(cm)		------------------------------(%)---	------------------------------	
Red Zone 1					
Crater Bottom	10	7.10	26.8	No Data	No Data
	20	7.86	6.8	0.69	0.69
	30	8.23	1.8	0.34	0.34
	50	8.68	0.4	0.08	0.08
Crater Side	10	7.98	5.5	0.58	0.57
	20	8.08	2.5	0.44	0.43
	30	8.53	1.4	0.48	0.48
	50	8.65	0.6	0.10	0.10
Undisturbed	10	7.45	7.4	21.15	18.97
	20	7.87	4.8	24.90	22.06
	30	7.93	4.5	12.09	11.43
	50	8.02	2.8	1.73	1.71
Red Zone 2					
Crater Bottom	10	7.58	8.6	2.03	2.01
	20	7.83	3.7	1.66	1.65
	30	8.09	1.8	0.81	0.81
	50	8.46	0.5	0.14	0.14
Crater Side	10	7.86	6.3	1.09	1.08
	20	7.97	2.1	0.51	0.51
	30	8.27	1.3	0.31	0.31
	50	8.63	0.6	0.18	0.18
Undisturbed	10	7.86	6.4	3.69	3.64
	20	7.87	4.9	2.21	2.19
	30	7.94	3.8	2.58	2.56
	50	8.25	1.8	1.02	1.02
Red Zone 3					
Crater Bottom	10	7.28	26.7	No Data	No Data
	20	7.84	8.6	1.03	1.03
	30	8.03	5.3	0.83	0.83
	50	8.25	1.5	1.13	1.13
Crater Side	10	7.45	13.2	No Data	No Data
	20	7.76	6.5	2.58	2.56
	30	7.97	2.7	1.50	1.50
	50	8.54	0.7	0.18	0.18
Undisturbed	10	7.22	6.0	24.08	21.78
	20	7.71	4.2	14.81	14.01
	30	7.73	3.2	2.71	2.69
	50	8.20	1.1	0.66	0.66
Bois de Thill 1					
Crater Bottom	10	5.58	16.6	10.69	10.22
	20	5.87	12.2	11.94	11.48
	30	6.82	2.6	14.23	13.72
	50	7.23	2.2	14.46	14.07

Appendix D (con't)

Crater Side	10	6.02	10.40	12.98	12.51
	20	6.41	3.30	14.43	14.07
	30	6.99	2.30	5.18	5.10
	50	7.85	2.20	14.53	14.28
Undisturbed	10	5.55	5.9	16.88	15.72
	20	6.26	4.0	18.76	17.52
	30	5.54	3.7	17.60	16.50
	50	6.77	2.5	13.80	13.40
Bois de Thill 2					
Crater Bottom	10	5.61	11.4	14.06	13.50
	20	6.69	4.3	16.68	16.22
	30	7.05	3.3	16.46	16.00
	50	7.96	1.9	3.06	3.04
Crater Side	10	5.11	6.4	16.33	15.75
	20	5.92	4.7	16.92	16.39
	30	6.99	3.9	17.95	17.30
	50	7.47	2.9	12.71	12.51
Undisturbed	10	4.34	7.8	23.31	22.28
	20	4.70	6.1	21.87	20.94
	30	5.97	3.8	18.91	18.21
	50	6.75	2.6	17.68	17.19
Bois de Thill 3					
Crater Bottom	10	7.09	8.1	13.22	12.61
	20	7.22	7.8	14.97	14.15
	30	7.20	4.4	14.83	13.73
	50	7.62	3.5	3.13	3.06
Crater Side	10	7.43	5.9	10.91	10.58
	20	7.43	2.5	3.00	2.97
	30	7.50	2.0	10.10	9.97
	50	7.62	2.1	13.90	13.66
Undisturbed	10	5.97	5.9	21.82	20.46
	20	6.27	3.5	22.75	21.77
	30	6.49	2.9	20.22	19.43
	50	8.09	0.9	0.68	0.67
Etraye 1					
Crater Bottom	10	7.38	15.2	3.05	2.98
	20	7.48	11.6	2.72	2.65
	30	7.58	8.4	1.88	1.85
	50	7.65	3.3	1.11	1.10
Crater Side	10	7.54	18.6	1.96	1.93
	20	7.74	3.9	0.79	0.79
	30	7.97	2.0	0.57	0.57
	50	8.00	1.3	0.52	0.51
Undisturbed	10	7.37	6.4	17.96	16.47
	20	7.44	5.5	19.57	18.04
	30	7.67	4.6	16.35	15.33
	50	7.91	2.1	0.87	0.87
Etraye 2					
Crater Bottom	10	7.33	15.6	5.11	4.92
	20	7.43	12.0	5.28	5.10
	30	7.55	4.2	4.30	4.22
	50	7.81	2.9	1.14	1.13

Appendix D (con't)

Crater Side	10	7.41	7.8	17.73	16.52
	20	7.50	7.0	14.40	13.57
	30	7.58	5.5	7.90	7.59
	50	7.71	5.1	4.53	4.39
Undisturbed	10	7.29	10.2	10.03	9.51
	20	7.52	5.5	15.94	15.01
	30	7.61	4.6	16.18	15.33
	50	7.72	4.1	11.98	11.46
Etraye 3					
Crater Bottom	10	6.88	31.0		
	20	7.24	20.3	3.13	3.06
	30	7.74	3.2	5.20	5.14
	50	7.74	2.7	3.58	3.56
Crater Side	10	7.53	7.6	6.53	6.37
	20	7.85	2.9	2.02	2.00
	30	7.83	2.7	2.13	2.11
	50	7.96	2.9	3.33	3.28
Undisturbed	10	7.41	9.2	12.97	12.33
	20	7.50	4.2	18.94	18.05
	30	7.75	3.7	20.96	19.85
	50	7.97	2.3	1.53	1.51

Appendix E: XRF data for soils and sediments

Site and Pedon	Depth	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	Rb	Sr	Zr
	(cm)	--------------------					(%)				--------------------		(PPM)	
Red Zone 1														
Crater Bottom	10	---	---	---	---	---	---	---	---	---	---	---	---	---
	20	17.88	0.24	3.40	2.17	0.04	0.51	35.79	0.00	0.50	0.09	32	231	139
	30	11.04	0.15	2.16	1.43	0.02	0.51	46.33	0.00	0.32	0.05	16	263	84
	50	4.21	0.04	0.42	0.51	0.01	0.45	52.91	0.00	0.08	0.02	0	226	25
Crater Side	10	16.47	0.21	3.00	1.60	0.03	0.51	37.59	0.00	0.49	0.08	27	237	121
	20	14.11	0.18	2.54	1.52	0.02	0.51	42.83	0.00	0.41	0.06	23	265	106
	30	16.52	0.20	2.81	1.72	0.02	0.54	43.56	0.00	0.48	0.05	21	265	122
	50	3.75	0.05	1.06	0.93	0.01	0.50	52.37	0.00	0.13	0.02	7	274	22
Undisturbed	10	60.06	0.80	10.45	4.72	0.07	0.79	1.79	0.29	1.42	0.10	84	76	461
	20	64.10	0.86	11.87	5.48	0.07	0.91	1.20	0.31	1.54	0.09	92	76	489
	30	59.72	0.82	13.80	6.98	0.08	1.15	4.37	0.23	1.61	0.10	114	95	417
	50	33.91	0.46	7.69	3.88	0.05	0.80	26.23	0.04	1.01	0.10	64	207	240
Red Zone 2														
Crater Bottom	10	34.92	0.45	6.50	3.34	0.06	0.49	21.99	0.00	0.95	0.12	61	181	249
	20	35.26	0.45	6.54	3.27	0.05	0.54	27.07	0.00	0.96	0.09	55	205	250
	30	24.35	0.30	4.09	2.13	0.03	0.43	37.83	0.00	0.68	0.07	36	263	168
	50	6.86	0.07	1.17	0.90	0.01	0.27	52.87	0.00	0.16	0.02	10	309	20
Crater Side	10	26.54	0.33	4.85	2.58	0.05	0.41	30.94	0.00	0.72	0.10	47	224	185
	20	17.97	0.21	3.16	1.79	0.03	0.36	42.35	0.00	0.48	0.06	26	268	111
	30	12.69	0.14	2.09	1.27	0.02	0.30	47.51	0.00	0.32	0.04	23	290	72
	50	8.80	0.09	1.38	0.96	0.01	0.28	50.90	0.00	0.21	0.03	12	306	41
Undisturbed	10	46.63	0.60	8.14	4.32	0.11	0.55	15.46	0.00	1.19	0.14	87	150	349
	20	39.83	0.50	6.86	3.82	0.09	0.49	22.47	0.00	1.00	0.13	69	181	292
	30	42.74	0.55	7.79	4.06	0.08	0.57	20.80	0.00	1.11	0.11	78	184	310
	50	27.43	0.35	5.38	2.72	0.04	0.52	34.76	0.00	0.80	0.08	52	253	177
Red Zone 3														
Crater Bottom	10	---	---	---	---	---	---	---	---	---	---	---	---	---
	20	24.81	0.30	4.21	2.29	0.05	0.39	29.60	0.00	0.69	0.11	43	212	171
	30	23.51	0.28	4.00	2.29	0.04	0.41	34.40	0.00	0.66	0.09	37	240	159
	50	30.98	0.37	5.25	2.60	0.04	0.53	32.98	0.00	0.94	0.08	44	237	206

Appendix E: (con't)

Crater Side	10	---	---	---	---	---	---	---	---	---	---	---	---	---
	20	40.58	0.52	7.32	3.61	0.06	0.57	19.62	0.03	1.10	0.11	67	170	296
	30	34.41	0.43	6.12	3.03	0.04	0.55	28.74	0.00	0.95	0.08	54	225	242
	50	8.70	0.09	1.38	1.02	0.01	0.31	51.16	0.00	0.21	0.02	13	280	42
Undisturbed	10	65.44	0.86	11.01	4.95	0.06	0.69	1.52	0.25	1.57	0.09	96	85	503
	20	62.45	0.83	12.99	6.27	0.08	0.91	3.36	0.17	1.64	0.09	109	92	454
	30	43.36	0.57	9.04	4.45	0.06	0.70	20.30	0.02	1.18	0.10	74	174	305
	50	21.83	0.26	3.80	1.96	0.03	0.44	40.46	0.00	0.62	0.06	34	266	143
Bois de Thill 1														
Crater Bottom	10	51.39	0.46	7.77	3.35	0.02	1.03	2.09	0.00	1.40	0.19	71	57	232
	20	59.78	0.53	9.08	4.18	0.02	1.23	1.79	0.00	1.63	0.17	84	62	254
	30	70.03	0.59	10.31	7.28	0.08	1.47	0.96	0.03	1.91	0.05	81	55	274
	50	71.85	0.61	10.36	5.06	0.04	1.49	0.98	0.03	1.95	0.05	80	57	290
Crater Side	10	62.70	0.56	9.55	3.74	0.02	1.26	1.59	0.01	1.67	0.14	81	58	269
	20	69.82	0.59	10.23	5.63	0.05	1.39	1.02	0.01	1.88	0.05	83	55	292
	30	62.52	0.54	9.76	5.90	0.07	1.45	7.64	0.02	1.80	0.08	75	106	237
	50	72.58	0.62	10.61	5.32	0.04	1.53	0.97	0.00	1.96	0.04	87	58	281
Undisturbed	10	68.48	0.65	9.27	4.60	0.09	1.13	1.14	0.08	1.79	0.13	92	59	354
	20	69.89	0.68	9.53	4.77	0.08	1.10	0.89	0.10	1.83	0.09	96	57	365
	30	71.02	0.68	10.48	5.38	0.10	1.28	0.87	0.09	1.91	0.08	100	55	344
	50	71.23	0.62	11.41	5.52	0.09	1.62	1.03	0.00	2.04	0.05	98	54	272
Bois de Thill 2														
Crater Bottom	10	60.13	0.55	8.84	3.95	0.02	0.95	1.65	0.00	1.50	0.15	79	69	264
	20	68.21	0.62	9.60	8.29	0.02	1.04	1.15	0.03	1.71	0.06	84	61	304
	30	67.70	0.60	9.60	10.29	0.06	1.10	1.02	0.00	1.71	0.05	88	59	303
	50	55.44	0.48	8.69	4.38	0.05	1.15	13.66	0.00	1.56	0.06	71	110	217
Crater Side	10	65.14	0.59	9.40	5.82	0.02	1.04	1.08	0.00	1.67	0.12	87	62	289
	20	65.38	0.60	9.20	7.54	0.02	0.97	1.14	0.00	1.61	0.10	84	62	293
	30	67.76	0.64	9.41	8.49	0.07	0.97	1.05	0.00	1.72	0.07	96	66	313
	50	69.56	0.61	11.24	6.25	0.04	1.42	1.68	0.00	1.93	0.04	93	64	294

Appendix E: (con't)

Undisturbed	10	70.06	0.72	9.15	4.37	0.03	0.87	0.56	0.00	1.82	0.12	104	61	376
	20	70.42	0.70	9.22	4.42	0.04	0.89	0.68	0.00	1.80	0.11	101	61	371
	30	70.65	0.71	10.22	5.04	0.07	1.06	0.99	0.00	1.89	0.08	110	65	349
	50	70.92	0.71	11.02	5.41	0.06	1.22	0.98	0.00	1.99	0.06	113	66	310
Bois de Thill 3														
Crater Bottom	10	65.45	0.60	8.77	4.59	0.02	0.94	2.27	0.00	1.57	0.21	80	65	319
	20	65.86	0.61	8.71	4.80	0.02	0.91	1.89	0.00	1.49	0.23	71	64	322
	30	69.60	0.63	9.61	6.12	0.12	1.01	1.80	0.00	1.66	0.24	90	65	331
	50	53.65	0.48	8.02	5.81	0.07	0.97	13.69	0.00	1.42	0.29	74	103	231
Crater Side	10	67.27	0.62	8.87	4.06	0.02	0.95	3.39	0.00	1.65	0.17	85	70	338
	20	55.74	0.48	7.87	3.87	0.07	1.01	14.20	0.00	1.52	0.10	71	114	222
	30	71.62	0.60	10.06	4.16	0.03	1.35	2.89	0.00	1.99	0.05	82	74	290
	50	73.51	0.61	10.39	4.76	0.03	1.38	1.26	0.00	1.96	0.05	84	60	294
Undisturbed	10	70.94	0.68	7.85	4.03	0.08	0.69	1.00	0.01	1.62	0.13	84	62	422
	20	74.89	0.72	8.63	4.43	0.07	0.80	0.84	0.00	1.72	0.08	94	64	443
	30	73.90	0.70	9.68	5.28	0.09	0.97	0.90	0.00	1.79	0.06	97	63	402
	50	28.67	0.24	4.14	2.54	0.07	0.65	35.56	0.00	0.84	0.05	34	185	105
Etraye 1														
Crater Bottom	10	34.10	0.49	9.18	6.70	0.11	0.85	14.22	0.00	1.67	0.32	100	172	210
	20	31.93	0.46	9.03	6.57	0.11	0.83	15.22	0.00	1.59	0.32	99	179	193
	30	29.26	0.41	9.14	6.11	0.08	0.90	20.27	0.00	1.53	0.29	94	223	162
	50	24.37	0.34	8.25	5.77	0.07	0.91	29.34	0.00	1.35	0.20	83	300	121
Crater Side	10	30.55	0.44	8.13	6.01	0.10	0.83	21.01	0.00	1.50	0.25	87	225	181
	20	18.89	0.28	6.09	5.17	0.08	0.80	34.67	0.00	1.08	0.15	62	334	99
	30	14.88	0.23	5.14	4.50	0.06	0.80	39.64	0.00	0.96	0.11	53	353	72
	50	13.64	0.21	5.24	4.84	0.07	0.80	40.14	0.00	1.00	0.11	50	374	61
Undisturbed	10	69.60	0.83	11.61	7.92	0.16	0.91	1.64	0.00	2.30	0.28	132	69	410
	20	62.03	0.86	12.41	8.41	0.16	0.96	1.26	0.00	2.39	0.23	142	68	420
	30	60.75	0.84	12.88	8.85	0.15	1.02	1.95	0.00	2.42	0.21	140	77	413
	50	20.81	0.30	8.02	6.28	0.07	0.94	33.15	0.00	1.27	0.13	80	317	91

Appendix E: (con't)

Etraye 2													
Crater Bottom	10	37.56	0.53	11.57	7.44	0.09	0.88	7.83	0.00	2.03	0.32	121	114	186
	20	39.20	0.56	12.88	8.31	0.09	0.99	7.80	0.00	2.17	0.29	133	115	185
	30	42.86	0.62	15.70	10.27	0.10	1.29	10.95	0.00	2.59	0.21	156	153	183
	50	25.82	0.34	8.24	6.34	0.07	0.74	28.84	0.00	1.35	0.19	90	304	117
Crater Side	10	58.92	0.84	12.47	7.55	0.13	0.85	1.69	0.00	2.41	0.23	135	71	374
	20	56.63	0.81	13.19	8.20	0.13	0.91	2.51	0.00	2.45	0.23	143	81	353
	30	49.42	0.69	15.10	10.50	0.14	1.14	5.40	0.00	2.52	0.23	156	104	261
	50	40.75	0.53	17.73	13.73	0.13	1.47	7.94	0.00	2.63	0.24	182	105	153
Undisturbed	10	48.90	0.69	11.75	7.87	0.13	0.83	4.16	0.00	2.18	0.26	126	91	290
	20	59.50	0.84	13.06	8.08	0.14	0.89	2.21	0.00	2.41	0.20	141	82	381
	30	61.27	0.86	13.57	8.30	0.13	0.95	2.04	0.00	2.56	0.18	149	79	382
	50	54.19	0.82	17.28	10.38	0.12	1.37	2.62	0.00	3.07	0.20	174	83	256
Etraye 3													
Crater Bottom	10	---	---	---	---	---	---	---	---	---	---	---	---	---
	20	26.89	0.39	8.21	4.43	0.03	0.59	10.75	0.00	1.51	0.29	85	126	125
	30	47.05	0.77	15.67	7.27	0.05	1.34	10.84	0.00	3.01	0.13	149	142	198
	50	42.48	0.69	14.06	6.73	0.05	1.23	15.85	0.00	2.68	0.11	129	173	183
Crater Side	10	49.04	0.71	12.55	7.20	0.08	0.97	7.94	0.00	2.36	0.21	132	118	264
	20	34.37	0.52	10.17	6.41	0.07	0.91	23.75	0.00	1.95	0.15	96	214	162
	30	34.70	0.52	11.34	7.33	0.07	1.01	22.02	0.00	2.06	0.16	112	225	153
	50	40.81	0.63	14.16	8.49	0.07	1.21	15.65	0.00	2.58	0.21	135	190	170
Undisturbed	10	56.76	0.79	11.34	6.52	0.12	0.78	3.34	0.00	2.25	0.21	125	83	359
	20	66.54	0.92	11.49	6.41	0.12	0.72	2.09	0.00	2.29	0.13	126	79	457
	30	66.02	0.90	13.34	7.53	0.13	0.92	1.04	0.00	2.53	0.12	145	71	410
	50	30.01	0.45	9.28	5.81	0.06	0.89	27.70	0.00	1.74	0.16	92	262	127

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