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Title Page

Assessing the role of slope, lithology and land use in the formation and conservation of war-related geomorphic features (case study of WW1 railway artillery in Montagne de Reims, Marne, France)

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Abstract

This contribution proposes to analyze a single archaeological object crossed by different conservation processes, to isolate and understand the role of geomorphological parameters in the formation and the conservation of anthropogenic geomorphic features. For these purposes, this study characterizes the remnant morphologies of the WW1 railroad in the Montagne de Reims on the western front (France, Rheims sector) through LiDAR-derived digital terrain models combined with archival documents (maps and historical photographs), spatial analysis and field surveys. This study shows that the Heavy Railway Artillery (*Artillerie Lourde sur Voie Ferrée - ALVF*) is a significant morphogenic feature, preserved at more than 70%. However, this morphology is subject to a strong variability. Ruggedness analysis shows a much more pronounced morphology on the slopes than on the plateaus, demonstrating a difference in formation and preservation processes. For formation processes, the study's findings reveal that geotechnical constraints related to lithology and geomorphology can be overridden for military purposes. For conservation processes, they are largely dependent on land use practices. This research demonstrates that ~~the role of geomorphological parameters in the interpretability of features is predominant, even if the war overrides natural processes for military purposes.~~ (i) the role of landscape and topographical parameters in the interpretability of features is predominant; (ii) military engineering has been able to adapt to a much diversified topography.

Keywords

Railway; LiDAR; World War 1; Anthropogenic Geomorphology; ~~War Landscapes~~
Polemoforms; Montagne de Reims

CRedit author statement

Robin Perarnau: Writing - Original Draft, Supervision, Conceptualization, Methodology, Validation, Formal analysis, Investigation, Visualization. **Alain Devos:** Writing – Original Draft, Supervision, Conceptualization, Methodology, Validation. **Amélie Quiquerez:** Writing – Review & Editing, Conceptualization, Methodology, Validation, Formal analysis. **Jérôme Brenot:** Writing – Review &

Editing. **Pierre Taborelli**: Investigation. **Sarah Ortonovi**: Methodology, Formal analysis, Investigation. **Bruno Furlani**: Investigation.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Abstract

This contribution proposes to analyze a single archaeological object crossed by different conservation processes, to isolate and understand the role of geomorphological parameters in the formation and the conservation of anthropogenic geomorphic features. For these purposes, this study characterizes the remnant morphologies of the WW1 railroad in the Montagne de Reims on the western front (France, Rheims sector) through LiDAR-derived digital terrain models combined with archival documents (maps and historical photographs), spatial analysis and field surveys. This study shows that the Heavy Railway Artillery (*Artillerie Lourde sur Voie Ferrée - ALVF*) is a significant morphogenic feature, preserved at more than 70%. However, this morphology is subject to a strong variability. Ruggedness analysis shows a much more pronounced morphology on the slopes than on the plateaus, demonstrating a difference in formation and preservation processes. For formation processes, the study's findings reveal that geotechnical constraints related to lithology and geomorphology can be overridden for military purposes. For conservation processes, they are largely dependent on land use practices. This research demonstrates that ~~the role of geomorphological parameters in the interpretability of features is predominant, even if the war overrides natural processes for military purposes.~~ (i) the role of landscape and topographical parameters in the interpretability of features is predominant; (ii) military engineering has been able to adapt to a much diversified topography.

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Polemiforms; Montagne de Reims

Abbreviations & Symbols ¹

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ALVF: *Artillerie Lourde sur Voie Ferrée* – Heavy railway artillery

DEM: Digital Elevation Model

GIS: Geographic Information System

LiDAR: Light Detection And Ranging

TPQ: *Terminus Post Quem*

°: angle degrees

m: meters

mm: millimeters

%: percent

px: pixels

Main text

1. Introduction:

Anthropogenic geomorphic features on landscapes can provide a widespread of relevant scientific content for both geomorphology and archaeology, such as the formation of anthropic landscapes and the ecological setting of ancient sociocultural processes, at the condition of understanding how those geomorphological legacies are formed through time. Studying complex man-made landscapes alterations provides new empirical and theoretical frameworks to work with (Tarolli et al., 2019), developing the construction of an interdisciplinary science of Anthropogenic geomorphology (Li et al., 2017).

Anthropogenic geomorphology, as a heritage science, is crossed by a fundamental question: how an object of study in the present time, is the result of previous complex processes of formation, and what are these processes? This regressive analysis approach of landscape reconstruction allows us to apprehend a society as well as man-made landscapes as close as possible from their initial state, avoiding a misleading interpretation of the archaeological environment as seen through the present ecological setting (Rivera-Collazo et al., 2021).

Former studies have studied the implication of geographical conditions in the development of archaeological sites. The influence of environmental factors in the anthropization of a territory (Shi et al., 2019; Dutt et al., 2019), or in site formation processes (Martínez et al., 2019) has already been analyzed, but not in the formation of a single archaeological feature. The effects of erosion on archaeological sites are documented (Kincey et al., 2017; Howland et al., 2018; Pourkerman et al., 2018) but rather on a regional scale.

As a contribution to these research efforts, this paper proposes to analyze a single archaeological object crossed by different conservation processes, in order to isolate and understand the role of geomorphological parameters in the formation and the conservation of anthropogenic geomorphic features.

For these purposes, the study of a railroad can be considered as defined by the same temporality but covering a large spatial extent and thus crossing different geographical contexts. Our choice focuses on a railroad built in a short window of time during the First World War, revealed by an airborne Lidar campaign in 2018. For this study, interdisciplinary work combining history, physical geography and archaeology was necessary, as a contribution to anthropogenic geomorphology.

The First World War (1914-1918) has impacted the landscape in the long-term. In four years 1.3 billion artillery shells were fired by belligerents causing a deep reshaping of the terrain. Studies dealing with the **morphological imprint** **archaeological remains** of the Great War focused on the most visible and characteristic forms of trench warfare such as trenches, mine craters, and bombshells using photo-interpretative methods (Stichelbaut et al., 2009) and spatial analysis of the trenchmaps (Combaud et al., 2016; Devos et al., 2015; Taborelli et al., 2018) that depicts landscapes devastated by the conflict (Amat, 2015). In cultivated areas, the legacies of these **morphologies structures** appear to be taphonomic and are investigated by archaeological studies (Brenot et al., 2017; Desfossés, Jacques & Prilaux, 2008), geophysical surveys (De Smedt et al., 2013), or remote sensing studies (Saey et al., 2013). **These "conflict-induced landforms"** (De Matos-Machado et al., 2019), **archaeological heritage resulting from the war's impact on the landscape, are referred to as "polemoforms"** by Amat (1987) and De Matos-Machado et al. (2019) from the Greek word *pólemos* (war).

On the western front, French forests, that are still bearing the scars of war, have been particularly studied over the last ten years by airborne Light Detection And Ranging (LiDAR)

image analysis (Hesse, 2014) in the Argonne defense networks (Taborelli et al., 2017b), in Verdun (De Matos Machado et al., 2016), in Rheims (Devos et al., 2019), in Flanders (Gheyle et al., 2018), and on the tunnel warfare sites (Taborelli et al., 2017a). However, to date, the **morphological footprint vestiges** of the railway itself has been poorly analyzed, except for rare studies in archaeological contexts (Devevey, 2014; Hillinger et al., 2001; Saunders, 2007, p. 142), or on ancient aerial photographs (Stichelbaut et al., 2009, p. 174). Considering the railway's morphological footprint as a separate and individual entity is made difficult by the fact that these **forms polemoforms** were most often erased by the continuity of human occupation. Additionally, in the few studies focusing on the railway's **morphological footprint remains**, it was analyzed through the prism of the structures associated with it (e.g. stations, depots). Historical studies dealing with rail during the Great War are therefore rare, and are generally restricted to emblematic subjects (for example 1914 mobilization (Lepage, 1996), the Second Battle of the Aisne (Geagea, 2012)), technical, for example the use of the metric track (Puig, 1996), political and/or socio-economic aspects (Caron, 2005; Desplantes, 1995; Ellenberger, 1975; Prévot, 2014; Roden, 2014), or even railwaymen (Lebrun, 2004), without involving the environmental and spatial dimensions. Historical geography studies on railway networks in the Great War focus on questions of economic flows at regional, national or cross-border scales (Prévot, 2017), some of them incorporate Geographic Information Systems (GIS) (Martí-Henneberg, 2017; Morillas-Torné, 2012).

As a method, GIS can be used in a diachronic analysis approach. This methodology is often used for the comparison of remote sensing data (e.g. Digital Elevation Model (DEM), high-resolution imagery), historical maps and field investigations. Such approaches can be developed for different purposes: landscape management (Cillis, Statuto & Picuno, 2021), geomorphological survey (Bisson et al., 2021), enhancement of urban heritage (García-Esparza & Altaba Tena, 2020) or archaeological investigations (Bachagha et al., 2020).

This contribution characterizes the **geomorphological landscape** legacies of the railway, behind the front zone, in a forest area in the Rheims sector, where an airborne LiDAR campaign, carried out in 2018, has revealed the traces of the 1917 railway network associated with the Heavy Railway Artillery (*Artillerie Lourde sur Voie Ferrée – ALVF*, hereafter). In this work, we study the railway footprint on the landscape and analyze the variability of the relict forms of the railway in various geomorphological and geological contexts. Combining analysis of textual and cartographic archives with the interpretation of the shapes from images derived from LiDAR data through a ~~Geographic Information System (GIS)~~, we identify a single archaeological structure, defined by the same temporal unit but covering a large spatial extent, and make it possible to discuss the role of the **geomorphological topographic** parameters in the conservation of this archaeological feature.

1.1. Study Area

The Montagne de Reims (Marne, Basin Paris), located 18 km south of the front line (Figure A and B), is covered by a large forest massif. Occupying the back slope of the cuesta of the Ile de France, it is composed of Eocene to Oligocene geological formations (Ypresian to the Rupelian rocks), overlying the Cretaceous Champagne chalk (Figure M). It is a wet plateau covered with Siliceous Clay recording higher precipitation (800 to 900 mm) than in the Champagne plain (700 mm). It is divided into three distinct and narrow plateaus (Saint-Basle, Ville-en-Selve and the Chêne à la Vierge) separated by the valleys of the Germaine and the Livre. These plateaus culminate at 286 m and overlook the city of Rheims and the valley of the Vesle by nearly 200 m. This valley comprises many witness buttes and outliers (Nogent-l'Abbesse or Mont de Berru) carved in Champagne chalk and fortified by the Séré de Rivières system between the end of the 19th century and 1914.

Lower Ypresian clayey beds, Upper Ypresian sands, and Lutetian and Bartonian limestones, that are outcropping in the front of the cuesta and in the valley, are affected by mass movements. These valleys are used by the railway line from Epernay to Rheims (Germaine Valley), by the road network, and by the Aisne to Marne canal to cross the Montagne de Reims.

Figure A

Figure B

1.2. Historical Context

August 1914 was marked by violent episodes of the Movement war, with German armies penetrating several hundred kilometers into French territory. Although the French counter-offensive of the First Battle of the Marne defeated the Schlieffen-Moltke plan and caused many casualties, it also led to the establishment of a new front extending from Switzerland to the North Sea. In the Rheims sector, the front stabilized in September 1914. The defense networks expanded to reach their maximum density in 1918 with four positions of several lines of trenches, located on either side of the no-man's land, over a total of nearly 40 km (Devos et al., 2015). The spatial analysis of the trenchmaps shows that this organization was along the front line, which was fixed on the Champagne Mountains and the Vesle River in the Rheims suburbs (Devos et al., 2015).

During the trench warfare, the French offensives in Champagne (1915) and on the Chemin des Dames (1917) had only local effects on the defense system. Only the first German positions were taken, which explains the hypertrophy of the networks of the first two French positions in 1918. The positions being fixed, it is a true artillery duel that is gradually taking place between the German positions on the Champagne Mountains and the French positions on the hills of the Montagne de Reims. However, the French militaries are poorly equipped in heavy artillery in the Rheims sector. Thus, Philippe Pétain, General of the Center armies at the time, insists on the necessity of developing the positions on the Montagne de Reims at the end of 1916 (Service historique, 1931, pp. 116-117). Concurrently, the regrouping of the heavy artillery (Service historique, 1937, pp. 181-182; Goya, 2014, p. 292) in the Aisne and Champagne enabled the preparation of the spring offensive. The Headquarters plan, including the construction of railways and firing positions for the heavy artillery, was achieved in early April 1917 (Service historique, 1937, p. 183). The heavy artillery could thus be used in the Second Battle of the Aisne (16 April-24 October 1917). The development of the railway network was of key importance in the strategy of Nivelle and Pétain, to be used for the rapid transport of high-powered pieces across the various fronts (Service historique, 1937, p. 183).

In this context, the actions initiated in 1916 by the Grand Quartier Général (GQG) for the development of ALVF led the French army to build positions on the Montagne de Reims to destroy the German fortified positions on the Monts de Champagne (François, 2017, p. 1).

Although a first four-branch firing epi (Figure C) was built from May 19th to July 2nd, 1916 south-east of the Germaine station (François, 2017, p. 2; Ministère des Armées, 1918, f. 23), the construction of the new network was stopped in the autumn of 1916 and began again on November 20th, 1916. This work included the construction of a ramp with an average slope of 78 mm/m over a length of 1035 m, completed on April 1st, 1917 on the Montagne de Reims (Ministère des Armées, 1918, f. 25).

Figure C

The ALVF remained operational until October 1918 on the Montagne de Reims but in a discontinuous manner, the network being partially dismantled during the German offensive of May 27th, 1918. Indeed, the Blücher-Yorck offensive broke the front to the west of Rheims to settle on the Marne, forming the Château-Thierry pocket. However, the Rheims sector resisted, with only the first French position taken. The western part of the Montagne de Reims, bypassed by the Germans, constituted a strongly defended lock (Alcaix, 2012). The French counter-offensive of July 1918 reduced the German pocket. The city of Rheims was liberated at the beginning of October 1918.

Miller's (1922) book gives more information on the construction of the railway. Tracks are of different dimensions depending on whether they are main tracks (Figure D.1.A), access tracks, sidings (Figure D.1.B), or firing tracks (Figure D.1.C). Gun type also influences network construction. In the case of the Montagne de Reims network, the 320 mm parts are mounted on non-traversing mounts (Figure D.2.A) with sliding (Figure D.2.B), which requires the construction of curved tracks for firing adjustment. These curved firing tracks, called "epis", can be doubled or quadrupled to allow multiple guns to fire simultaneously. These firing epis are then arranged in forceps (Figure D.3.A, 3.B, 3.C, 3.D) or palms (Figure D.3.E, 3.F). To ensure that a firing track can support the firepower, it is reinforced with eight beams. These beams are grouped in pairs and aligned parallel to the central lane.

Figure D

1.3. Spatial Analysis from Archives Data

The two German maps (*Artillerie Karte*) of June 19th and July 3rd, 1918 (Figure E) allow to describe the structuration of the French railway network of the Montagne de Reims ("Grosser Bergwald"). **These maps were georeferenced using ground control points and a polynomial transformation (affine) that preserves collinearity and allows scaling, translation and rotation only.** The narrow east-west orientated railway Tacot lines (in blue and red) are linking the three plateaus (Le Chêne à la Vierge, Ville-en-Selve, Saint-Basle) and are connected to the north-south oriented Craon de Ludes line. The network of ALVF, which has a total development of 26 km, is established from the railway tunnel of Rilly-la-Montagne (on the civilian line between Epernay and Rheims). This tunnel is located at an elevation of 180 meters above mean sea level (m.a.m.s.l.) and a multi-track "combat garage" can be identified in the surroundings. The junction with the ALVF line is made with a steep ramp that allows to reach the plateau at an elevation of 270 m.a.m.s.l. into a single track (siding line).

Figure E

This track uses the Craon de Ludes ridge where it follows the narrow track of the Tacot to interconnect the plateaus of Ville-en-Selve and Saint-Basle. It serves groups of multi-branched (or double), curved epis using the flatness of the plateaus. The curved epis are structured in palms with a group of height branches on the Ville-en-Selve plateau (François, 2017). To the east, on the Saint-Basle plateau, there are two groups forming a forceps of four-branch curved firing epis (for 320 mm pieces, according to François (2017)) and a group of straight double epis. Straight epis on the plateau of Ville-en-Selve and at the Craon de Ludes pass probably used lighter 190 mm or 210 mm artillery pieces. In the Germaine valley, at the north-east of Germaine village (hamlet of Vaurémont) two double epis, built in 1916 for 320 mm pieces (François, 2017) and listed on a German map of July 3rd, 1918 remain detectable on the aerial photographs of 1949.

The analysis of the German maps shows that the ALVF line has been supplemented by two flak artillery posts at Craon de Ludes, a high concentration of barracks in the Germaine valley close to the two double epis (Vaurémont sector), and an ammunition depot located to east of the central palm position on the access road.

2. Materials & Methods

The combined analysis of the data of the trench maps drawn up by the German Headquarters in June and July 1918, old and recent aerial photographs from the Institut national de l'information géographique et forestière (IGN), the Landesarchiv of Baden-Württemberg, the Service Historique de la Défense (SHD) and the Bibliothèque Nationale de France (BnF) as well as the topographical data (LiDAR 50-cm, RGE ALTI® 5-m and BD ALTI® 75-m) (Appendix A), allows to carry out a diachronic study of the **morphologies polemoforms** to analyze the evolution of their conservation state since 1918. All this data was integrated and processed into a **Geographical Information System GIS** (Figure F).

Table 1

Figure F

A 50 cm **Digital Elevation Model (DEM)** was derived from a 245 km² airborne LiDAR campaign (Office National des Forêts (ONF) and the Parc Naturel Régional de la Montagne de Reims (PNR-MR)) performed in the winter of 2018 (Appendix B) at an average altitude of 550 m. The average point density is 12 points per m², the relative positioning accuracy is 25 cm and the relative height accuracy is 10 cm. Topographic indices (hillshade, slope, Sky View Factor (SVF), Positive Openness (Open-P)) were obtained using the *Relief Visualization Toolbox* (Kokalj & Hesse, 2017; Kokalj & Somrak, 2019; Zakšek, Oštir & Kokalj, 2011) to detect small-scale archeological features. Local Relief Model (LRM) (kernel size: 25 m) was also calculated using the Toolbox for ESRI ArcGIS 10.2 (Novák D., 2014, this work refers to Bofinger & Hesse, 2011 and Hesse, 2010) (Figure G). These index calculations were supplemented by a ruggedness index estimation to better highlight the vestiges of the ALVF (Riley, De Gloria & Elliot, 1999). The ruggedness index was calculated from a 10 m resolution DEM, derived from the 50-cm LiDAR DEM over a 20-m buffer zone centered on the ALVF trace. The ruggedness index is defined as the median value of the differences between the central pixel and the surrounding cells.

Figure G

3. Results

In this section, we describe ~~the initial spatial organization of the railway network based on archival documents from 1918, and~~ the inherited ~~morphologies~~ ~~geomorphologies~~ revealed by the LiDAR to discuss the preservation processes.

3.1. Traces of a heavy artillery railway network

If the ALVF network had already been described by François (2017) from their representation on German maps, the LiDAR images reveal the footprint of this construction in the landscape in the long term (Figure H). The network highlighted by the LiDAR data is overall well preserved since 18.7 km long track out of the original 26 km can still be detected. These preserved vestiges include a ramp of nearly one kilometer and about 8 km of curved tracks, associated with firing epis. However, the other four curved tracks, which are attested by archival documents and old aerial photographs in the Germaine valley south of the Rilly railway tunnel, are not detected by LiDAR, suggesting that they may have been destroyed by post-occupation developments.

Figure H

The curved tracks are grouped in two groups, one on the plateau of Ville-en-Selve (palm barriers consisting of eight tracks) and the other on the plateau of Saint-Basle (two groups of four curved tracks structured as forceps and one group of two straight routes further south). The siding line linking the different firing tracks is remarkably well preserved and seems to be doubled on the crest of the Craon de Ludes. The ramp linking Germaine station to the Ville-en-Selve plateau is also ~~a morphogenic structure, with elevations reaching up to several meters high and therefore easily identified on images from LiDAR data.~~ easily identified on images from LiDAR data.

3.2. ~~Transversal morphologies~~ Cross-sections profiles of ALVF

The numerical terrain model derived from LiDAR reveals the presence of ~~longitudinal roads~~ ~~railroad tracks~~ at the location of the ALVF network determined by the archival data, but it also ~~shows the extent of terracing through cross-sectional profile analysis~~ allows a cross-sectional profile analysis to discriminate between cuttings and embankments (Figure I). These structures are characterized by an average width ranging from 10 to 20 meters, with a height reaching up to 2 meters. The cross-sectional profiles reveal a 5 m wide planar surface at the location of the central lane, two ditches on either side of the lane, and a bulge along the ditches. The morphological footprint of the central track is only limited to the embankment because the rail and ties have completely disappeared, presumably dismantled for post-war re-uses. This footprint is not only slightly detectable in the landscape, it is also spatially very variable due to the undulating morphology of the plateau.

The residual traces on flat or gently sloped terrain (firing tracks) are relatively minimal (Figure I.3, I.4, I.5 and I.7), with an amplitude less than 50 cm, and hardly differentiable from recent or old roads in the field (Figure J.1, J.2, J.3 and J.4). Conversely, the ramp of the inclined plane is easily identifiable with an amplitude of several meters (Figures I.1, I.2 and Figure J.5.). Cross-sections through the ramp highlight specific shapes defined by excavations reaching up to 5 m on the interfluves (Figure I.1) and by several meters' high embankments on the valley slopes (Figure I.2).

The siding section located on a hillslope at the Craon de Ludes (Figure I.6) is also well preserved, as it is shown by the cross-section profiles revealing metric elevation differences including an upslope ditch and a platform downhill.

Figure I

Figure J

3.3. Ruggedness index of ALVF

Spatialization of the ruggedness index values reinforces the detection of the ALVF morphologies on LiDAR images (Figure K). It demonstrates the spatial heterogeneity of the morphological footprint of ALVF by differentiating the vestiges located on the plateaus (Sectors 2 and 4) from those located on the slopes (Sectors 1 and 3). The distribution of ruggedness values (Figure L) allows to distinguish two types of sectors. The values in sectors 1 and 3 are much more dispersed, with higher values than in sectors 2 and 4 (see Table A). Finally, a Conover-Iman test comparing values of ruggedness by sectors shows a strong similarity within Sectors 1 & 3 and Sectors 2 & 4 (see Table B).

Results of LiDAR data analysis show a difference in the preservation of the railway, with vestiges presenting lower relief on flat terrain than on slopes. Such differences could not be only explained by different erosion processes since slope vestiges are better preserved.

Figure K

Figure L

Sectors	1	2	3	4
Median (Average)	0.16	0.08	0.18	0.08
Mean (Average)	0.19	0.1	0.21	0.09
Standard Deviation (Average)	0.11	0.05	0.12	0.05

Table A: Central values of Ruggedness index by sectors.

	Sector 1	Sector 2	Sector 3
Sector 2	32.67430	/	/
	(p-value < 0.01)	/	/
Sector 3	-1.633973	-53.19469	/
	(p-value = 0.0511)	(p-value < 0.01)	/
Sector 4	36.86808	7.769210	59.59501
	(p-value < 0.01)	(p-value < 0.01)	(p-value < 0.01)

Table B: Conover-Iman test comparing values of Ruggedness index grouped by sectors.

4. Discussion

By combining archival documents and images from the Airborne LiDAR, this work contributed to document the history of the railways, located behind the French fourth position (Reims sector). But also, those results have revealed some significant spatial differences of the railway footprints that are discussed hereafter. Among the possible causes, these differential preservations could be due both the local geotechnical choices at the time of construction of railway but also to the post-war land-use, and indirectly to geomorphology, and lithology.

4.1. Geomorphological & Geotechnical constraints

The **geomorphology topography** is one of the major factors that can explain the spatial difference of morphologies inherited of the ALVF observed between the three sections, that is the ramp, the siding line at the Craon de Ludes pass, and the shooting epi from the plateaus.

The access ramp, exhibiting a strong **geomorphological** trace, is excavated into contrasted geological formations (Figure M.2). The ramp passing through the Germaine valley and the Rilly-la-Montagne tunnel, and which is served by the line between Epernay and Reims, recovers a difference in height of almost 80 m over less than one thousand meters. The ramp successively crosses, from the valley to the plateau, the Thanetian sands, the Lower Ypresian clays, the Upper Ypresian sands, the Lutetian white marls, and the Bartonian limestones and finally the Siliceous Clay of the plateau. However, this geological factor is not binding for military engineers, in contrast to the geomorphological context, as a regular and steep slope (7.8 %) alternately crosses valleys separated by small interfluves. This results in high relief features such as deep **excavations cuttings** in the interfluves and important embankments in the valleys.

Figure M

The geomorphological context influences the type and location of the structures. It appears that firing tracks are always installed on the remnants of plateaus, where the slope is gentle, although the soil is loose and wet and thus requires additional landscaping, as lateral ditches to drain the hydromorphic and muddy soils developed on Siliceous Clay (Figure M.3; Figure I.3, I.4, I.5 and I.7). Textual archives confirmed some of the considerable difficulties linked to supplementary construction works, showing the predominant choice of the morphological position rather than of the unsuitable substrate (François, 2017).

Therefore, we suppose that the construction of the ALVF requires flat terrain to accommodate multi-track firing epi, gentle and regular slopes for rail transport, but also relatively dry and stable ground to support the considerable load of 160-ton artillery pieces. In the case of the Montagne de Reims, these conditions are spatially variable with a geomorphological context of plateaus dissected by deep valleys, hydromorphic nature of the soils, which requires considerable construction works, explaining a high preservation of the ALVF network (70%).

Archive analysis suggests a predominant role of geotechnical choices made by French engineers. The structure of railroad depends not only on geographical constraints but also on its functionality (freight, passenger transportation, military use) (Lefevre & Cerbelaud, 1889).

LiDAR images analysis shows that the vestiges of the ballasted platform carrying the track display widths ranging from 10 to 20 m, at the firing epis. However, the expected width for such platform is of the order of 5 m, in accordance with the Military Engineer's instructions (Ecole de chemins de fer, 1916; Salin, 1876). We suppose that largest width satisfies local geotechnical constraints to carry 32-cm gun slides mounted on jacks and supported by four lines of 2-m long girders, that are laid on the track ties and parallel to the rails (Figure D.1.C;

Miller, 1922; Ministère de la Guerre, 1927). Other evidence of developments and terracing, that were not initially planned, suggest the necessity to accommodate the construction plans to the local conditions. These include, for example, some terracing and drainage systems that have been conducted to maintain regular and gentle slopes necessary for the transport of artillery pieces. We have also noticed that the roadbed is bordered by 30-cm deep ditches to drain water to the closest valleys, and to prevent water pockets from accumulating in the ballast.

Similarly, the crossing of valleys and interfluves must have led the geotechnical engineers to massively excavate or backfill on sloping terrains (Figure N). Therefore, the difference in ruggedness observed between flat and sloping terrain seems to be the result of geomorphological constraints present prior to construction. However, as Caron (2005, p. 536) points out: “The history of railways during the war was thus a succession of emergency measures, [...] which did not always take sufficient account of the geographical constraints that weighed on the configuration of the lines [...]”. All these observations show that the military imperative takes precedence over geotechnical constraints. This duality between military imperatives and geotechnical constraints is particularly present during the construction of such structures. The observations of this study clearly show the prerogative of military interest over the difficulties of the terrain.

Figure N

4.2. Post-war land use history

The post-war land use history has a strong influence on the preservation of the footprint. For example, the roads that have been constructed since the end of the conflict may overlay the tracks belonging to the ALVF. Consequently, the preservation of the ALVF footprints may be altered or mixed up with other traces, making it difficult to recognize them in some areas, as it is the case on the siding track area on the Ville-en-Selve plateau or on the firing epi area in the Germaine Valley (Figure H).

Exacerbated soil erosion due to easily erodible substrate combined to silvicultural practices can result in strong spatial heterogeneity of the residual relief. The preserved topographic anomalies of the siding line illustrate such variability. The siding line is better preserved at the head of the Livre valley, at the Craon de Ludes pass, where Upper Ypresian formations outcrops, which are more draining and more resistant than the Siliceous Clay of the plateau (Figure M).

Significant differences in preservation may also be related to the vegetation cover. It appears that tracks are much better preserved under a forested cover context than in cultivated areas (Figure O). And yet, our data reveal that the topographical footprint of the ALVF in cultivated areas may have totally disappeared (Figure O.11). Phytographic anomalies on aerial images bear the last traces of the presence of the ALVF structure. For instance, it was not possible to detect on the LiDAR images the firing tracks located near Pomacle (Marne) whereas a regressive analysis of old aerial photographs shows gradual deletion of the firing tracks, as the result of erosion processes and agricultural practices. Such preservation difference between cultivated and forested areas is particularly observable when comparing the firing tracks of Pomacle and Ville-en-Selve.

The group of firing epis at Ville-en-Selve is no longer detectable in aerial images, due to densification of the canopy, whereas, at Pomacle, the soil cultivation contributes to the removal of the traces, leaving only slight phytographic evidence.

Figure O

Agrarian practices and the reoccupation of tracks (roads or railways) jeopardize the conservation while the development of protected forest areas, as it is the case for the Montagne de Reims, results in the fossilization of archeological remains and facilitate the development of scientific studies and heritage enhancement programs.

These differences in preservation of archaeological remains between forested and agricultural areas are found at other recent conflict sites. Indeed, the multiplication of lidar surveys on forest areas in recent years show protective zones for archaeological remains related to conflicts. For the First World War, this is obvious in Verdun (De Matos-Machado & Hupy, 2019; De Matos-Machado et al., 2019), and for the Second World War, in the northwest of France (Passmore, Harrison & Tunwell 2014) and in the Netherlands (Schriek & Beex, 2017). Recently, Zalewska and Kierszys (2021), who have a study area with very different land uses, also note the much better preservation of remains in areas under forest cover.

Finally, this work highlights the question of the morphodynamic evolution of ~~war morphologies~~ ~~forms~~ ~~po~~ ~~lemo~~ ~~forms~~ since the end of the conflict. This study is a first step towards a quantification of the degradation rate of railway morphologies, an additional step would be to extend the archaeological data by field excavations. The rates of degradation of WW1 remains have already been addressed in dug or plain areas from shell craters or trenches (Brenot et al., 2017). Unlike trenches or shell craters, the low morphogeneity of railway tracks on plains or plateaus may suggest a greater vulnerability of these ~~forms~~ ~~po~~ ~~lemo~~ ~~forms~~ to silvicultural or agrarian practices, as well as to geomorphological constraints. Paradoxically, the destruction by the transformation of the ALVF's route into a path, road or forest layon, a phenomenon already observed on the Montagne de Reims, makes it possible to preserve a long-term footprint of this heritage.

5. Conclusion

The ALVF requires flat ground for the development of the epi, stable ground to support the important load of the guns and draining ground to avoid flooding and the bogging down of the artillery pieces. The construction of a complex network (ramp, 18 km of tracks, numerous firing tracks) in a context of forest plateaux, clayey and incised by deep valleys subject to numerous ground movements required an impressive construction site for the time (François, 2017) with heavy earthworks. The morphological footprint of the ALVF remains paradoxically small in wartime landscapes but still remains in this particular context. Conversely, in cultivated plains, the morphological markers disappear in favor of phytographic clues following recultivation.

While this network is complex, it is nonetheless limited to positional warfare. The systematic orientation of the firing tracks towards the North was to render their use obsolete after the German offensive of May 1918 which bypassed the Mountain of Reims from the West, especially as they were spotted by the Germans. Just like the Séré de Rivières forts in the defensive belt of Rheims, which were badly oriented and far too easy to spot (Devos et al., 2019), these heavy investments by the French army would become useless or unsuitable for maneuver warfare.

This study provides a better understanding of the ~~rail's morphological footprint on~~ **archaeological remains of the railway in** the landscape. These unprecedented results contrast with the emblematic vestiges presented by the research of recent years in contemporary archaeology and war landscapes studies. Indeed, these traces of the fourth defensive position are faint if compared to the remains of defense networks found in the front lines (trenches, casings, bunkers, shelters). Difficult to observe in the field, but revealed by LiDAR technology, they require special visualization techniques (LRM, ruggedness index) to be readable. Like the other polemoforms, they are preserved under forests but attenuated by erosion and sedimentation.

Scheduled archaeological excavations would make it possible to characterize not only the geomaterials used for earthworks but also the morphogenetic evolution of the Great War railway lines over the past century. In-depth studies are also essential to understand the facilities annexed to the construction and the operation of the ALVF (geomaterial quarries, stations, cantonments, combat garages, observation sites, defense against aircraft, ammunition depot). Finally, the study of the railway footprint through time is a further step towards a better understanding of military-industrial landscape alterations through a multidisciplinary approach.

As a contribution to the science of anthropogenic geomorphology, the role of geomorphological parameters in the interpretability of anthropogenic geomorphic features has been discussed as a predominant parameter both in their formation and in their conservation through time. However, this study shows that the military-industrial phenomenon, and even more so war, overrides natural processes in a specific way for military purposes.

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Figure Captions

All figures are provided for a full-page width in double-column (190 mm).
Color should be used for online only.

Figure A: Localization. **1.** Geological Map of the Western Front with localization of the Study area. **2.** Localization of LiDAR campaigns in relation with Great War defensive systems.

Figure B: Map of Study Area showing Global DEM Slope (%) data. Elevation data extracted from BD ALTI® 75 m (copyright "© IGN – 2018").

Figure C: Battery position of French army 320 mm howitzer on firing epis near Thillois (near Rheims (Marne - 51) in April 1917. Université Paris X-Nanterre, coll. La contemporaine VAL082-048, ARK:/14707.

Figure D: Railway artillery systems, according to Miller (1922).

- **1.** Profiles type for Main Lines (**1-A**), Sidings (**1-B**) and Firing tracks (**1-C**).
- **2.** Methods of traverse, recoil and anchorage systems for French army 320 mm howitzer, similar to those used on the Mountain of Rheims.

2-A. Non-traversing mount.

2-B. Sliding recoil.

2-C. Truck platform.

- **3.** Firing tracks systems

3-A, 3-B, 3-C, 3-D. Variations of "Forceps" type.

3-E, 3-F. Variations of "Palm" type.

Figure E: Excerpt from the German Master Plan (*artillery karte*) of 19 June 1918 (Coll. Fort de la Pompelle, Ville de Reims).

Figure F: Development of the Geographic Information System.

Figure G: Comparison of visualization methods used to reveal ALVF structures.

- **1:** German Trench Map (1918).
- **2:** Aerial Photography (1949).
- **3:** Visualization from LiDAR derived DEM - Analytical Hillshading (Parameters: Sun Azimuth: 315°; Sun Elevation Angle: 35°; Histogram Stretch: Linear (0-1)).
- **4:** Visualization from LiDAR derived DEM – Slope gradient (Parameters: Histogram Stretch: Linear (0-51°)).
- **5:** Visualization from LiDAR derived DEM – Anisotropic Sky View Factor (Parameters: Main direction: 315°; Number of search directions: 16; Search radius: 10 px; Level of Anisotropy: Low. Histogram Stretch: Equalization (2% cut-off)).
- **6:** Visualization from LiDAR derived DEM – Openness positive. (Parameters: Number of search directions: 16; Search radius: 10 px; Histogram Stretch: Linear (60-95°)).
- **7:** Visualization from LiDAR derived DEM – Local Relief Model (Parameters: Low pass filter radius: 25 m).
- **8:** Visualization from LiDAR derived DEM – Local Relief Model (Parameters: Low pass filter radius: 25 m); Opacity: 50%. Analytical Hillshading (Parameters: Sun Azimuth: 315°; Sun Elevation Angle: 35°; Vertical Exaggeration: 5; Histogram Stretch: Linear (0-1)).
- **9:** Visualization from LiDAR derived DEM – Local Relief Model (Parameters: Low pass filter radius: 25 m); Opacity: 50 %. Slope gradient (Parameters: Vertical Exaggeration: 5; Histogram Stretch: Linear (0-51°)).
- **10:** Digitalization and Interpretation based on precedent visualizations.

Figure H: Detection of the railway system. Cross profiles are described in Figure I. Terrain contour lines extracted from BD ALTI@ 25 m (copyright “© IGN – 2017”).

Figure I: DEM-derived images and ALVF network profiles. 1&2: ramp. 3,4&7: firing epis. 5&6: siding line. For the localization of the profiles, see Figure H.

Figure J: Photographic plate of listed structures from a pedestrian survey (1, 2, 3: July 2019; 4, 5: May 2019). 1: Firing epi (Plateau de Saint-Basle). 2: Firing epi (Plateau de Saint-Basle). 3: Firing epi (Plateau de Saint-Basle). 4: Firing epi (Plateau de Ville-en-Selve). 5: Ramp. The topography is particularly observable by the orientation of the trees.

Figure K: Map showing the relation between cell data of Ruggedness-Index (meters) on the railway path, and global DEM Slope (%) data.

Figure L: Histograms and boxplot from cell data, showing the distribution of Ruggedness-Index values (in meters, from 0 to 1) in the different Sectors (for localization, see Figure K). Data extracted from 10*10 meters grid, according to LiDAR DEM-derived data of Elevation (meters).

Figure M: 1. Geological long profile of the ALVF route. 2. Geological block diagram of the access ramp to the Plateau of Ville-en-Selve. 3. Geological block diagram of the siding line at the Craon de Ludes pass. Geological data extracted from BD Charm-50 (copyright “© BRGM – 2005”).

Figure N: Cross-sections showing the work required to build a railway track on steep terrain (according to Lefevre & Cerbelaud, 1889). a: Embankment; b: Natural ground; c: Excavation. On a slope *b*, earthworks can be presented in three ways: 1-Placement of allogenic backfill; 2-Discharge of the slope to provide backfill to support track; 3-Digging in the slope forming a gutter.

Figure O: Aerial photographs and DEM of the Firing Epis located in cultivated areas, near Pomacle (Marne), and under forest cover, near Ville-en-Selve (Marne).

1. 1918 (TPQ), according to Grand Quartier Général des armées (1918).
2. 1917, According to Landesarchiv Baden-Württemberg, Abt. Generallandesarchiv Karlsruhe 456 F 7 Nr. 724 Foto 9 Bild 1.
3. 1949.
4. 1949.
5. 1957.
6. 1957.
7. 1962.
8. 1963.
9. 2011.
10. 2011.
11. 2015. Visualization from LiDAR derived DEM (Cellsize: 5 meters) – Analytical Hillshading (Parameters: Sun Azimuth: 315°; Sun Elevation Angle: 35°; Histogram Stretch: Linear (0-1)). LiDAR data from RGE ALTI@ 5m (copyright “© IGN – 2015”).

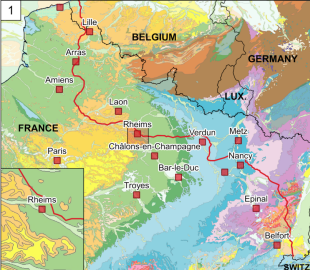
12. 2018. Visualization from LiDAR derived DEM (Cellsize: 0.5 meters) – Analytical Hillshading (Parameters: Sun Azimuth: 315°; Sun Elevation Angle: 35°; Histogram Stretch: Linear (0-1)). Original LiDAR data.

Apart from 1. and 2., all aerial photographs were provided by the *Institut national de l'information géographique et forestière* (IGN), through the website "*Remonter le temps*". See Appendix A for more information.

Appendices

Appendix A: Cartographic data used.

Appendix B: Technical specifications of LiDAR survey.



Defensive system before May 1918

Triple-Alliance's trenches

Triple Entente's trenches

"Séré de Rivière" Forts

City of Rheims

LIDAR Campaigns

1 Zone of Rheims Campaign (2015)

2 Mountain of Rheims Campaign (2018)

A - Plateau of Chêne à la Vierge

B - Plateau of Ville-en-Selve

C - Plateau of Saint-Basle

Altitude (meters)

<= 50

50 - 100

100 - 150

150 - 200

200 - 250

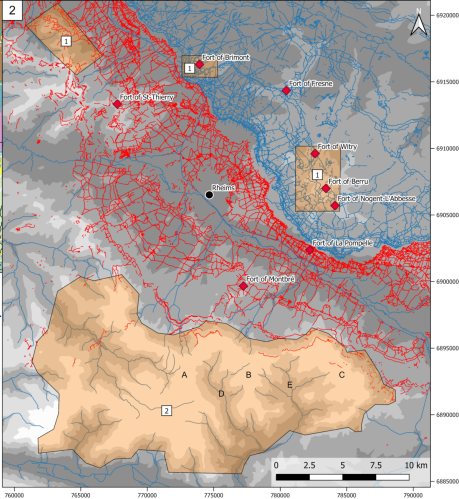
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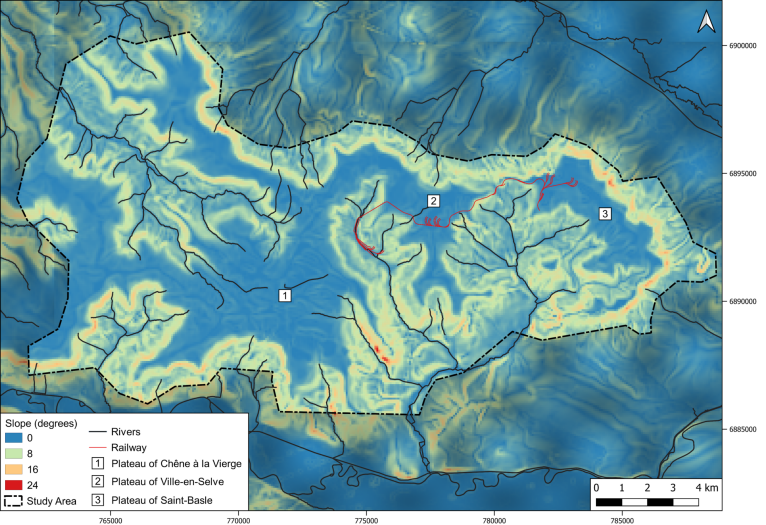
Rivers

D - Valley of Germaine

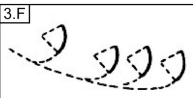
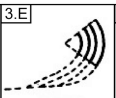
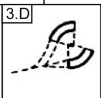
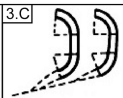
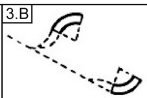
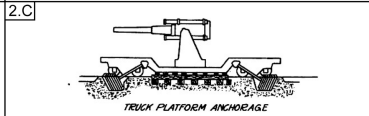
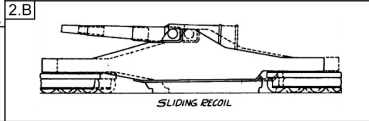
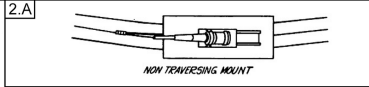
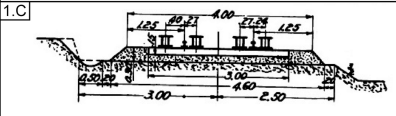
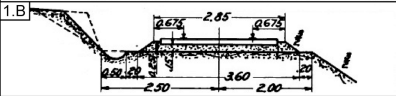
E - Valley of Livre

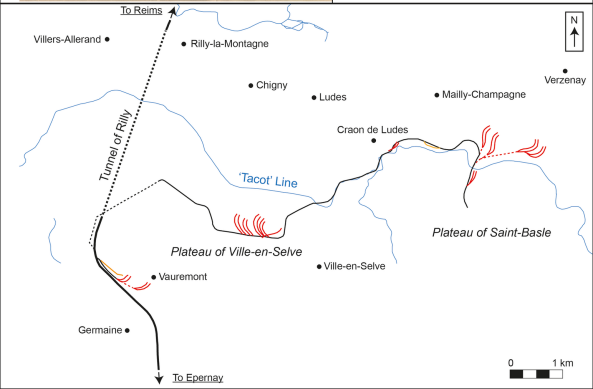
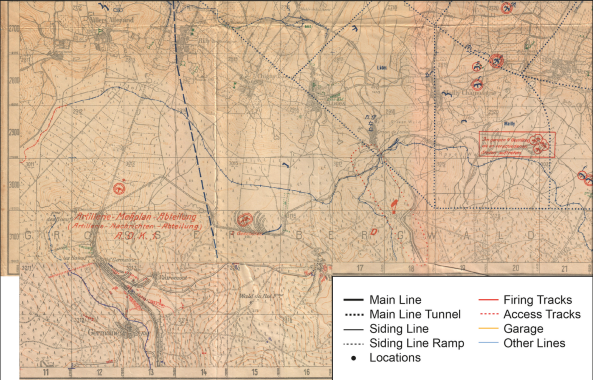
DEM data : IGN/BD ALTI® v2.0 25m/2021
Geological Data : BRGM/BD Million-Géol/2019
Hydrographical Data : IGN/BD TOPO®/2018

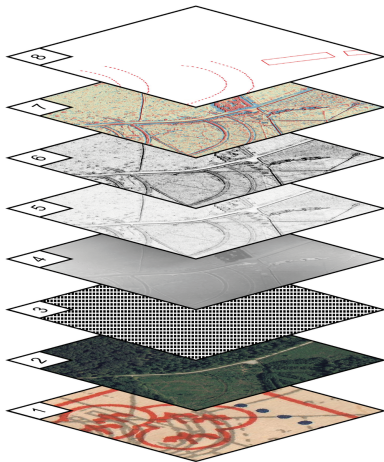




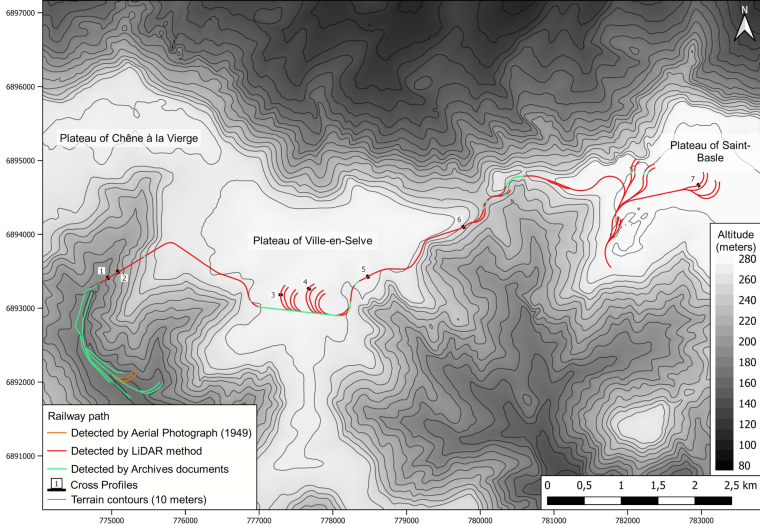




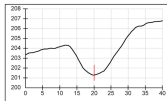
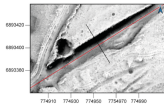




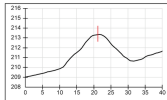
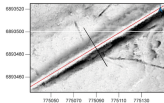
8. Features Extraction
7. Local Relief Model (50% opacity)
6. Histogram Stretch
5. Visualization Technique (e.g. Sky View Factor)
4. Digital Elevation Model
3. LiDAR Point Cloud
2. Orthophotographic Image
1. Archived Maps and Aerial Photographs



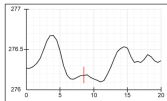
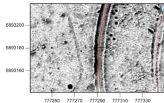
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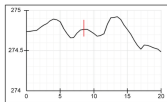
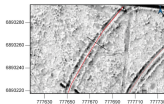
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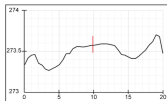
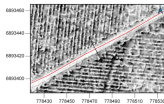
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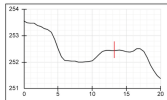
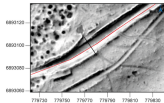
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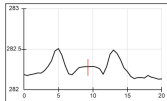
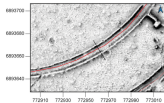
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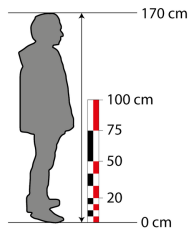
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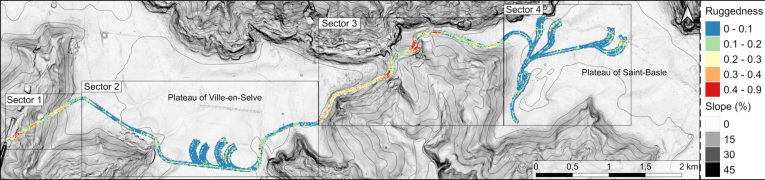


— Profil Line
— Railway path

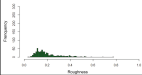
X-axis : Distance (meters)
Y-axis : Altitude (meters)

0 50 m

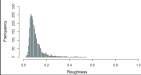




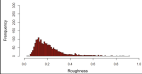
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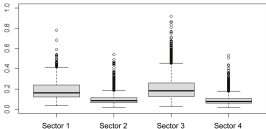
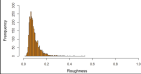
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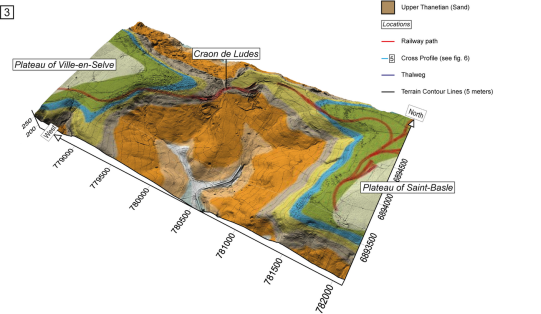
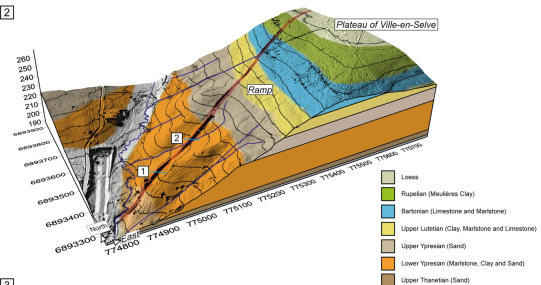
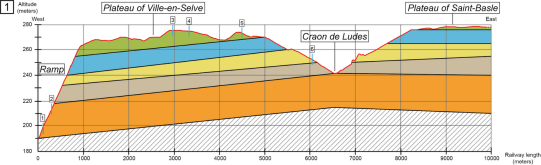


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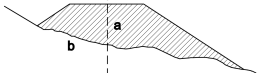


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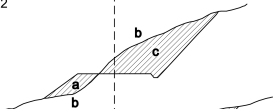




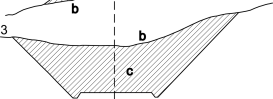
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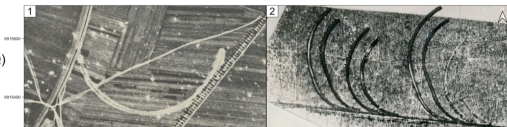
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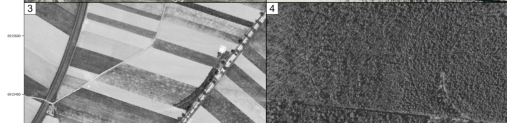
Pomacle

Ville-en-Selve

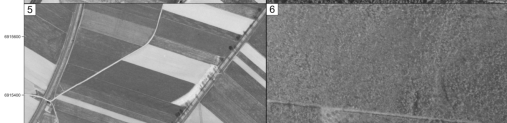
1. 1918 (TPQ)
2. 1917



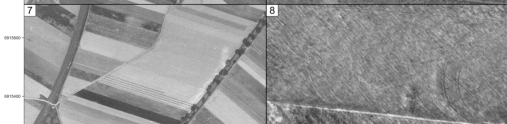
3 & 4.
1949



5 & 6.
1957



7. 1962
8. 1963



9 & 10.
2011



11. 2015
(DEM)
12. 2018
(DEM)



Sectors	1	2	3	4
Median (Average)	0.16	0.08	0.18	0.08
Mean (Average)	0.19	0.1	0.21	0.09
Standard Deviation (Average)	0.11	0.05	0.12	0.05

	Sector 1	Sector 2	Sector 3
Sector 2	32.67430	/	/
	(p-value < 0.01)	/	/
Sector 3	-1.633973	-53.19469	/
	(p-value = 0.0511)	(p-value < 0.01)	/
Sector 4	36.86808	7.769210	59.59501
	(p-value < 0.01)	(p-value < 0.01)	(p-value < 0.01)