Trench construction and engineering geology on the Western Front, 1914–1918

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Abstract: Trench warfare became associated with the First World War from late 1914 until 1918. Where possible, trenches were laid out by military engineers in line with the most recent military manuals. The effectiveness of individual trenches was to a large extent controlled by the nature of the ground conditions. Engineering geology had a major role to play in: slope stability—as the ideal for trenches was to maintain slopes in an over-steepened condition relative to normal angle of repose; and, drainage—as excess surface and ground waters not only weakened trench slopes but also created untenable conditions for the troops occupying their positions. Recent archaeological investigations around the city of Ypres (Ieper) in Belgium, and in northern France provide opportunities to examine slope engineering and drainage solutions for trenches in Palaeogene clay/silt sediments and Cretaceous chalk. In Flanders, the failure of slope engineering early war led to the creation of 'A' frames to support slopes at the required batter, with the provision of drainage channels beneath duckboard walkways. In northern France, where frost-shattered chalk was close to the surface, drainage and slope support was less of a problem, though trenches cut through thick Quaternary deposits similarly required imaginative solutions.

Trench warfare became associated with the First World War from November 1914. At this point, the Allied and German armies had become locked in a series of battles that saw them attempt to 'turn the flanks' in a phase of the conflict that became known as the 'race for the sea'. As both sets of armies approached the coast, so they began to construct trench lines that would remain largely static—though with some periodic movements in the wake of offensives—until 1918.

Though associated with the Great War, the adoption of trench lines in late 1914 owed much to at least two and a half centuries of application and development of the art of the military siege. Nevertheless, in 1914 the establishment of trench lines was effectively to produce two parallel fortresses that were exceptionally difficult to destroy (see Saunders 2010; Doyle 2017). These lines were in place from the end of the mobile phase in 1914, through to the opening of a new phase of open warfare in the spring and summer of 1918. Establishing and maintaining these trenches required much engineering skill. As excavations, trenches were inevitably subject to geological controls, and the engineering geology of these military fortifications became a major consideration in ensuring that they were 'fit for purpose' in static warfare, as first discussed in some detail by American military geologists Alfred Brooks (1920) and Douglas Johnson (1921) in the immediate post-war interval.

Trench warfare came to encapsulate not only the simple excavation of trenches for protection and defence, but also the development and construction of underground shelters (dugouts), concrete surface shelters (pillboxes), together with subways and tunnels for military use. Some work examining the geological aspects of these has been completed (e.g. Doyle *et al*. 2002, 2006; Rose & Rosenbaum 2011; Doyle 2012, 2015, 2017), and is on-going. Relatively little attention has been given to trenches themselves, however. As such, the aim of this paper is to examine the development of trenches and trench warfare in relation to geology within the northern sector of the Western Front (Fig. 1), as here it is possible to contrast the geological conditions of the chalk country of Artois and Picardy with that of the Flanders clay plain, with their attendant problems. Its focus in particular is the engineering geology challenges faced by the armies. Reference is made to the contemporary military manuals provided to British, and to a certain extent, German armies In addition, consideration of the resulting trench lines and their geology is made both through access to existing archive resources, but also through the examination of archaeological excavations in this region carried out over the past 25 years. These excavations show very clearly the way in which military engineers struggled to adapt their experience to the long-term occupation of the trench lines that were put in place from late 1914 to Spring 1918. (See Doyle *et al*. 2001, 2006; Barton *et al*. 2004; De Meyer & Pype 2007; Brown & Osgood 2009; Dewilde & Saunders 2009; Saunders 2011; Verdeghem *et al*. 2013; Doyle 2015, 2017).

Geology and trench warfare

The application of geology in war dates back some centuries (see Rose 2014), but arguably it was the work of German military fortification engineer Hauptmann (later Major) Walter Kranz that defined the principles of *Militärgeologie* (Kranz 1913; see also Häusler 2003), though Kranz's ideas were taken seriously only when war broke out in Europe (Brooks 1920, p. 91). A review of Kranz's work in 1915 laid down the basic principles of *Militärgeologie* ~~(Anon. 1915, p. 94);, which were built upon and expanded in a wartime lecture delivered by Wilhelm Salomon of Heidelberg University in 1915:~~

> Geology is practical and necessary: to prove the stability of parapets and trenches and the stability of dugouts; to identify the speed of digging excavations; to identify water supplies; to assist in rain water and waste water removal; to supply building materials; and to identify mineral raw materials (Anon.~~Salomon~~ 1915, p. ~~00~~94, translated)

These principles were built upon and expanded in a wartime lecture, *Kriegs-Geologie*, delivered by Wilhelm Salomon of Heidelberg University in 1915, and published in the same year (Salomon 1915).

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Trenches and dugouts clearly figure ~~in this~~in the definitions of the subject by Kranz and Salomon, as does the need to deal with waste waters that inevitably accompanied their excavations, both from groundwater build up, as well as surface-water flow and precipitation. Resolving some of the difficulties presented by the trench war formed much of the work of Allied and German military geologists, and these activities have been ably described elsewhere (e.g. King 1919; Brooks 1920; Institution of Royal Engineers 1922; Rose & Rosenbaum 1993; Häusler 2000; Rose *et al*. 2000; Willig & Häusler 2012; Rose 2014). This paper examines the evidence of this work, and of the geological challenges presented to them, and to the military engineers of the day.

Geology of Northern France and Flanders

The geology of Flanders-Picardy is not complex (Figs 2 and 3), but it was to have a major role in influencing the outcome of the war, and in the prosecution of trench warfare. As noted in 1917 by Sir Aubrey Strahan, the Director of the Geological Survey of Great Britain, direct geological comparison could be made between the region of France and Flanders, and that of southern England, with particular regard to the chalk, the Thanetian sands, and the clay of Flanders, so readily associated with the London Clay (Strahan 1917, p. 70)..

> That the chalk escarpments of the North and South Downs are continued in the chalk escarpments which overlook Boulogne is obvious, and that the subdivisions of the Tertiary strata with which we are familiar in the London and Hampshire Basins are recognisable in the North of France and in Belgium is well known. Not only so, but the scenery characteristic of each formation is reproduced with fidelity. (Strahan 1917, p. 00)

Military geographer Douglas Johnson (1918, 1922) studied the region and for convenience divided it into broad 'belts'. These belts have been discussed in detail by Johnson (1922) and used by others as a shorthand for the geology (e.g. Doyle & Bennett 1997; Doyle 1998, 2017; Doyle *et al.* 2000; Barton *et al*. 2004). In simple terms, from Belgian Coast to the Somme these fall into at least six zones or belts: the coastal dune belt; the Polder Plain; the clay plain; the sand ridges; the coal belt; and the chalk upland (Figs 2 and 3):

1. The coastal dune belt comprises a 2-km-wide strip of Holocene coastal dunes that fringe the North Sea. Each of the dunes is made up of loose

sands, though stabil~~ise~~ized by marram grass and other hardy vegetation typical of the sand hills along the North Sea coast (De Moore & Heyse 1978; Heyse 2015).

2. North of the Belgian city of Ypres, commencing for the most part at the village of Dixmude and passing north to Nieuport, is the coastal plain of Flanders, 'the Polders', an area regularly flooded during the Holocene that has been engineered to provide access to agriculture. The Polder plain is at best just five metres above sea level (De Moore & Heyse 1978; Heyse 2015) but farther south the clay upland provides a barrier to inundation by the sea. Across the coastal plain runs the Yser, joined and linked to the complex of artificial canals and drainage ditches between them. Not surprisingly, the polder plain is composed of a sequence of sands, silts and organic rich deposits, all of which are conspicuously water bearing. (see Doyle 1998, 2017; Baetman 1999).
3. From Ypres southwards, Flanders comprises an extensive, flat plain composed of thick deposits of clay, overlain by soils and other Quaternary deposits (De Moore & Heyse 1978; Heyse 2015). The plain itself is mostly made up of clays once traditionally called the 'Ypres Clay'—now the Kortrijk Formation (see Steurbaut & Nolf 1986; Steurbaut 1987; Nolf & Steurbaut 1990; King 1990; Laga *et al*. 2001; De Geyter *et al*. 2006; see also Rose & Rosenbaum 2011). This thick blanket of clay underlying the city of Ypres and spreading its influence across the region consists of heavy clays of variable depth, reaching up to 130 m thick, but reducing to around 50 m in the west. The clay is blanketed by Quaternary soils to a greater or lesser extent (see Heyse 2015), with considerable thicknesses of alluvium in river valleys.
4. Rising slowly up from the clay plain is a low range of hills that curve to the east of the city of Ypres. These low hills are part of a relict ridge system that has been sculpted by streams that flow onto the clay plain. This ridge had been occupied by the Germans from 1914, providing them with direct observation of their enemies on the plain. The low ridge system is composed of what contemporary geologists called the 'Paniselian sand complex', of Eocene–Pliocene age, named after Mont

Panisel near Mons, where it was first described in detail. The 'Paniselian' sediments overlie on the 'Ypres Clay', and consist of a stratigraphical sequence of sands, sandy clays and clays of variable composition and extent (see Laga *et al*. 2001; De Geyter *et al*. 2006). Today, the 'Paniselian' is defined in modern stratigraphical terms as belonging to the Gent Formation and lower levels of the Tielt Formation (see Steurbaut & Nolf 1986; Steurbaut 1987; King 1990; Nolf & Steurbaut 1990).

5. South of the Messines Ridge the ground descends from the Paniselian hills, first to the valley of the Douve, and then, farther south, to the Lys. These rivers flow over an extension of the clay plain, with at depth chalk deposits. Farther south into French Flanders, Carboniferous coal-rich deposits are found closer to the surface, due to the Marqueffles fault system. This is most obviously associated with the Vimy Ridge, a fault scarp that now divides Flanders from Artois and Picardy. Below surface, the geology is complex, with multiple thrust slices associated with the Variscan Orogeny (see Delattre *et al*. 1973).
6. Beyond Flanders, the Artois region comprises a broad anticline, an extension of the Weald. This chalk upland has, in contrast with the buried Lens Coalfield, a relatively simple, flat-lying structure. The chalk of the Somme and Artois is broadly equivalent to that of southern England and, like it, comprises three divisions: a lower, more clay-rich part (*les marnes crayeuses*), a middle, flint-bearing level (*la craie grise à gros silex cornus*, overlain by *craie blanche à silex*), and an upper, pure white, flint-poor part (*craies blanche*) (See Delattre *et al*. 1973, pp. 25–26; Bureau de Recherches Géologiques et Minières 1982). The chalk is mostly frost shattered in its upper part, and other evidence of the Quaternary is provided by the soil layers that lie above the white chalk. Typically there are four separate units: clay with flints, loess, loam, and alluvium, although not all will be present at any given location (see Johnson 1921). The loess and loam are often classified together on French maps as *Limons de Plateaux*—a fine covering on the upland areas, but sometimes reaching a thickness of up to 10 m. It forms a cap to the hill-tops and slopes, and helps to fill the valleys.

Trench warfare

The primary purpose of trenches as employed in the First World War was to hold the enemy until an assault could be deployed, and to protect their occupants (General Staff 1908, 1917*a*, *b*, *c*; see also Saunders 2010; Doyle 2017). However, as was experienced during the war, not all trenches were equal in value and effectiveness, and to a greater or lesser degree this was a product of geology and terrain. Trenches could suffer enfilade fire—the opportunity for an enemy to fire along their length—which was in part due to the method of construction, and the position relative to topography. They could be exposed to observation—again a function of slope and position—and their occupants again be vulnerable for this reason. And from a purely geological perspective, trenches could be perennially wet, flooded or flooding; they could be subject to collapse due to weakness in the rock mass, or through oversteepened and/or poorly-engineered slopes, and they could be exceptionally difficult to dig, dependant on soil cover (see Doyle 2017 for discussion).

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Though trench warfare was becoming a much more professional business by 1916, it is still important to understand that the situation and condition of Allied trench systems was often greatly influenced by their General Staff's offensive policies, and a general unwillingness to yield ground, in its early days at least. For the Allied General Staff there was a constant fear that trench warfare would engender a defeatist attitude, an 'unhealthy' dependence on shelter or safety, with 'an insidious tendency to lapse into a passive and lethargic attitude, against which officers of all ranks have to be on their guard, and the fostering of the offensive spirit, under such unfavourable conditions, calls for incessant attention' (General Staff 1916, p. 8).

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The Germans, on the other hand, had gained ground early in the war and were able to retain their position, through the maintenance of an overall defensive attitude. There was no squeamishness about maintaining strong positions. Their

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field manual, *Stellungsbau*, of 1916, translated by the British General Staff in 1917, made clear the principal considerations—and the commitment to attrition:

> Field positions when constructed afford considerable advantages to the defence. The important points to be borne in mind by the *defence* in a *war of positions* [includes]: utilization of ground so that conditions favourable for combat are obtained, while they are made unfavourable to the enemy (General Staff 1917*c*, pp. 3–4).

As a result, deep shelters—dug-outs—designed to protect troops from direct shellfire were mostly a feature of German defensive positions, while Allied positions had mostly small excavations in trench walls or, later, cut and cover shelters using corrugated iron and sandbags (see discussion in Brooks 1920; Johnson 1921; Doyle *et al*. 2001, 2006; Barton *et al.* 2004). All in all this meant in many cases that Allied lines were poorly situated with respect to topography and ground conditions, while German policy allowed for strategic withdrawal to carefully prepared and suitably located positions (see Doyle 2017 for review).

For the most part, similar trench systems were employed by the main protagonists on the Western Front, directed by their high commands, but influenced by experience on the ground. For example, a British manual published in 1916 gives a list of the typical components to give the maximum confidence of 'defence in depth.' (Lake 1916, p. 47; Fig. 4):

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1. Obstacles—generally barbed wire—in front of first line trench, concealed if possible from artillery observation.
2. Listening posts, look-out posts, machine guns.
3. Fire trenches, recessed and traversed.
4. Communication trenches to the rear, linking up the whole system.
5. Shelters and dug-outs. These should be immediately behind the first line fire trenches, with easy communication to them.
6. Support trenches—traversed—from 25 to 100 yards in rear of fire trenches.

7. Dressing stations, kitchen, etc., branching from communication trenches.
8. Second line trenches. Fire trenches, machine guns, etc., similar to organisation of first line.
9. Supporting points, behind second line, well defended by parties of 20 to 40 men, serve to hold up enemy assault on first and second line; such points should be entirely surrounded by barbed wire (Lake 1916, p. 47).

In ideal circumstances, trenches were to be planned, laid out and traced across ground so as to take in natural characteristics and use them to advantage, as well as avoiding difficulties presented by the local geological conditions. As the British *Field Defences* manual of 1908 wryly commented: 'The ideal site for trenches is one from which the best fire effect can be obtained, in combination with complete concealment of the trenches… As such positions will rarely be found, the best compromise must be sought for' (General Staff 1908, p. 48). For the German High Command, committed to ensuring their trench lines were the strongest, the use of natural features as strongpoints was the most important factor.

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> Great use has been made by the Germans of natural strong points, such as villages, farms, and woods. The normal procedure now, when taking up a new position, is to fix on a general line of natural strong points, and to prepare these for defence first and then to join them up by fire trenches, without much regard to the field of fire of the latter (General Staff 1917*a*, p. 17).

Trench types

In their simplest sense, the trenches of the Great War were linear excavations of variable depth that were mostly open to the sky, but were sometimes, rarely, roofed for concealment purposes (see Brooks 1920; Doyle 1998; Doyle *et al.* 2001). Despite their simplicity, the function of trenches varied and as the war progressed, with no absolute sign of a break in the deadlock, more and more types were developed. The pace of change was so rapid that the third edition of *The Royal Engineers Field Service Pocket-Book* of 1916 contained only blank pages for field defences, accompanied by the statement: ‘Owing to the constant changes taking place in Field Defences it has been decided… to omit this section which will be rewritten after the war…’. (Johnston 1916, p. vii). However, in the main there were two consistent types: fire trenches, which formed the front lines, and communication trenches, which joined them.

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Fire trenches (i.e. fighting trenches) were divided into a regular pattern of fire bays (facing the front, and occupied by soldiers on guard) and traverses (which linked the bays) (Fig. 4). This system meant that no soldier could walk in a straight line for long, without having to switch back on himself. Such movement was intended to limit the effects of shellfire exploding in the trenches, or from the possibility of enfilade rifle and machine gun fire along the length of a trench.

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British and German fire trenches were alike in this respect; French versions varied, some had a more leisurely, curved, zigzag—but all calculated to reduce the impact of explosions and enfilade fire. French military engineering was the inspiration for much of trench warfare. Thus, the spoil removed in digging a trench was used to form a ‘parapet’—a mound of earth in front of the trench on the enemy side, intended to stop bullets, and a ‘parados’—a slightly higher mound at the rear, which would interrupt the movement of bullets and reduce the impact of exploding shells, and prevent soldiers’ heads from being silhouetted against the skyline. ‘Firesteps’ were constructed to allow the infantry to fire over or through the parapet (General Staff 1908).

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Communication trenches (or CTs) varied in length. Running from the rear areas and connecting all the forward trenches up to the front line, they offered protection for supply and troop movements from the rear (Fig. 4). They were usually dug in a zig-zag or wavy pattern and in Flanders, where the geological conditions meant that revetment—officially defined as ‘any artificial material used for retaining earth at a steeper angle that it would normally assume’ (General Staff 1908, p. 39)—was essential, CTs had similar dimensions to a fire trench. In the coastal strip at Nieuport, communication trenches of French construction were close boarded and roofed by timber, and referred to as *boyaux couverts* (Doyle *et al.* 2001).

The front line trenches of the opposing armies were separated by a belt of contested ground known as 'No Man's Land', usually extensively pitted by shell holes and mine craters. In some cases, only mine craters lay between the two lines, and guidance on capturing and strengthening craters was given in all the manuals (War Office 1921; General Staff 1917*a*). Behind the frontline, some 10 to 30 m, were the support and reserve lines, trenches that were still 'organ~~ise~~ized for fire', with the intention of holding back the enemy if a break-through of the frontline had been achieved. Farther back were the reserve lines. The whole system could be encapsulated within a zone of 50 to 150 m width, and access from the rear areas to each of the trenches in turn was through communication trenches, which traversed the ground between the lines of fire trenches. In some cases, particularly where the enemy controlled the high ground, tunnels or subways were constructed to allow safe passage of troops to the front from the rear areas. This became a feature of the trench war in 1917 (see Doyle 2017 for discussion).

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Trench construction

Trench construction was usually carried out by the infantry (General Staff 1914). Fatigue parties and later labour battalions had mostly to dig their trenches rapidly under the cover of darkness, generally with men spaced between two to three paces apart. For the Germans, there were explicit instructions that the construction of trenches was to be entrusted to those men who would, at least at first, be occupying them, again under the control of engineers (General Staff 1917*c*, p. 4).

Speed of digging was directly influenced by ground conditions, prevailing weather, and the nature of the troops. The rate of digging was generally taken to be 30 cubic feet (*c.*10 cubic metres) per hour, increasing by 50% where soils were 'very easy' and decreasing by 30% where soils were 'very hard' (General

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Staff 1908, p. 14). For the most part, the geology of the battlezone in northern France and Flanders consists of variable thicknesses of Quaternary soils overlying soft sediments, clays, silts and sands. Where trenches were to be dug into chalk ground in Artois and Picardy, ground conditions could vary. In some cases Quaternary soils capped chalk spurs, in other cases, this had been removed, leaving a capping of bare chalk. In most situations, however, this chalk was extensively shattered by freeze-thaw, and therefore relatively easy to work.

With, in most cases, the Germans dictating the line of the opposing trenches, more often than not the trace of the British defences was unfavourable, but it is hard to general~~ise~~ize. For the British at least, there was little chance to reference the nature of the local geology. For the Germans the ideal was to have two types of geologist to advise: 'the trained ones who are of use in the field before and after the battle', and 'the officer on the front during battle' (Anon. 1915, p. 95).

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Position relative to slope was an important factor to be considered in the construction of trenches. Basic principles for entrenchment were laid down which emphas~~ise~~ized theoretical aspects of position in relation to forward and reverse slopes, valleys and spurs, and topographical height (Pressey 1919; War Office 1921, 1925). These aspects were considered important in order to allow effective observation of opposing trench positions, to prevent enemy observation of forward and reserve trenches, and to provide necessary supportive arcs of fire for small arms. Ideally, the trench lines were to be designed to contour hills and valleys, particularly important in providing 'mutual enfilade' fire in valleys, the assaulting troops being attacked from both sides of the valley, and on the slopes of spurs by the defenders (Pressey 1919; War Office 1921, plates 14, 15).

In all cases, the positioning relative to slope was to maxim~~ise~~ize observation of the enemy to direct artillery and machine gun fire. In the Ypres area, the British trench lines were positioned either at the foot of or, on the reverse slopes of, the 'Paniselian' (Gent Formation) ridge complex overlooking the Ypres clay plain. This made artillery observation difficult, and provided ample opportunity for

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accurate offensive fire from the German artillery. In the rolling Chalk upland of the Somme, British positions were more variably positioned, and more able to follow the guidelines laid down by the official regulations (see Doyle 2017 for discussion). But again, for the most part, the German lines were more formidably sited.

Slopes and revetment

As open excavations, trenches were subject to the normal considerations of slope engineering, as the 'required stability of rock slopes will vary depending on the type of project and the consequence of failure' and 'there is usually little flexibility to adjust the orientation of the slope to suit the geological conditions encountered in the excavation' (Wyllie & Mah 2005, pp. 1–2). In military trenches, more often than not constructed under fire and with little regard to best practice, the consequences of failure would bring obvious problems for those men seeking shelter, and, for the Allies in particular, there were few options available.

In the ideal situation, each fire trench approximately two metres deep, and 0.6 metres wide at the bottom, usually widening to two metres at its top, but depths varied according to topography and the depth to permanent water saturation. Trench width at floor level was around 0.8 metres, and at the top, given the appropriate regulation 'batter' or slope, up to three metres (Fig. 5). In official terminology, trench sides were known as 'slopes', and were routinely kept at over-steepened angles relative to the normal angle of repose for soft sediments. The British wartime manual of Field Defences, first published in 1908 was clear in its insistence that to be effective, the 'interior slope should be as steep as possible in order to increase the protection from projectiles falling at a steep angle' (General Staff 1908, p. 55). The same manual determined that 'in almost any type of soil, it should be possible, with sods, lumps of earth, or other means, to keep the slope up to $^{3}/_{1}$ for a moderate height; but unless great care be exerc~~ise~~ised, it will seldom be possible to build a slope steeper than $^{2}/_{1}$' (General Staff 1908, p. 55; Fig. 5). These gradients suggest slopes should be at least 65–

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70º, rather than the angle of ~~~50~~35º more likely to be achieved for clay soils, without some form of engineered stabili~~z~~sation methods. These were known as revetments, defined as 'any artificial material used for retaining earth at a steeper slope than that which it would naturally assume.' (General Staff 1908, p. 20).

In the case of trenches, with the requirement to maintain, steep slopes, some form of revetment to maintain the steepened slope was therefore essential, particularly in the soft sediments encountered in Flanders from the coast to the Marqueffles Fault Zone. While steep slopes in clay are possible for short periods, especially during dry weather, absorption of water would soon lead to slope failure. Periodic failure of slopes was to a certain extent to be expected given their purpose; this is not usually an acceptable aspect of the slope engineering within civilian projects (Wyllie & Mah 2005, p. 4). What is required is the establishment of a Factor of Safety (FS), the limit equilibrium of the slope, with stability achieved where the FS>1. Given that trenches were cut through a variety of materials, were subject to changes in pore pressure in permeable sediments, especially in the vadose zone above the level of water saturation, and suffered from the violence of explosions, this was not always an easy proposition. In addition, it has to be recogn~~ise~~ized that military trenches intended from the outset only to be a 'phase' of the military campaign as directed by the General Staff, and that detailed examination of their engineering geological aspects was singularly lacking in the early stages of the war. This would change as it was real~~ise~~ized that trenches had become a major component of the architecture of the war.

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With trench sides slopes cut at a higher angle than the soils could support naturally, to prevent collapse there was a real need for an engineered solution and revetment with whatever was available, sometimes wattle, often corrugated sheeting and expanded metal (xpm), sometimes chicken wire, or even timber boards if they could be salvaged (Fig. 6, see examples below). 'Brushwood' and 'well-built sods' were also recommended and used (General Staff 1908, 1917*a*,*b*, p. 12). Timber was often used to hold these materials in place, as were angle iron

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posts anchored deep into the earth; and layers of bonded sandbags strengthened the whole. The military manuals laid down the parameters:

> The side of trenches which have to be occupied for a long time, and particularly in wet weather on a damp site, must be reveted. Hurdles or rabbit netting held up by stout stakes securely wired to short pickets firmly anchored in the parapet or parados, form a useful type of revetment for this purpose. Sandbags are not so suitable. In the winter in Flanders some really solid form of revetment, such as planks or timber, or expanded metal sheets, is necessary (General Staff 1917*a*, p. ~~00~~12).

In addition, by 1917 to assist with the construction of trenches in 'soft ground', 'trench frames' were recommended in British use (Fig. 7, see examples below). The intention of the frames was to provide engineered support for over-steepened and often water-saturated slopes. The idea was that they would not only help retain the trench profile, but would also permit a firmer anchoring of the revetment materials, as well as a means of creating a walkway elevated above trench bottoms. The idea for the frames was published in the December 1916 revision to the earlier British manual '*Notes for Infantry Officers on Trench Warfare*', drawn up in March of that year. Such frames were an inverted 'A', the cross of which provided an elevated foundation for a duckboard track, and the main line of the 'A' providing a support for both the trench revetment, and the sandbag walls of a breastwork (General Staff 1917*a*, fig. 13; War Office 1921, pl. 69). Major Buckingham RE, Assistant Inspector of Mines, was equally impressed with them when he encountered the frames in a communication trench in 1917:

> I was very struck with this trench which is the most elaborate trench I have seen. It was made in accordance with recent E in C's [Engineer in Chief] plates with expanded metal revetment held in place by [inverted A] frames about 3' or 4' above duck board level & then a flat ledge, and unreveted sides above (Diary Major W.E. Buckingham RE, The National Archives file WO158/140).

The development of such structures indicate the need to deal with the unsupported and over-steepened slopes that were such a component of the trench war in 1914–15, with new engineering solutions widely adopted by 1917 at least.

Drainage

The provision of adequate drainage was obviously of great significance in the construction and maintenance of trenches. In extreme cases, particularly where thin soil cappings sit on clay and in other areas where groundwater was close to surface, 'borrow pits' were dug on either side of the trench to supply extra earth needed to build up a sufficient height to protect the troops. In some cases sandbag 'breastworks' were constructed where ground conditions prevented even the most rudimentary trench lines. Captain F.C. Hitchcock of the Leinster Regiment described his ideal trenches in the clay-ground near Armentières, in 1915:

> Our trenches appeared to be very formidable; they were duckboarded, and the parapets and paradoses were completely reveted with sand-bags. The parapets were 6 feet high, and the wooden fire steps being 1 1/2 feet in height, gave a fire position of 4 1/2 feet. Owing to the low-lying nature of the terrain the trenches were breastworks (Hitchcock 1937, p. 22).

Such breastworks (Fig. 8), known as 'high command' trenches, in contrast with the normal 'low command' types (General Staff 1908), were common in the Ypres Salient, due to usual water-logged nature of the Quaternary soils or Paniselian sands that overly the Kortrijk Formation. Digging down farther simply created a void, one lined with impervious clay, that would soon be filled with water, and which would require pumping against both groundwater and rainfall (Fig. 9).

Ensuring the trench was adequately drained and floored was clearly essential. On both sides, trenches were 'floored' with wooden duckboards, which were built up to allow drainage beneath—in fact it was common for successive levels of duckboards to be laid one on top of another to combat the difficult conditions encountered. In rare cases, bricks and rubble were used, when trench lines snaked through the destroyed villages and houses. While men hoping that waters would subside inside a flooded trench, this factor was at the mercy of ground conditions. As the British post-war *Manual of Field Works (All Arms)* was quick to point out: 'sumps or soakage pits should not be relied upon unless natural drainage is possible…unless the sump reaches a permeable stratum, it must be pumped or baled out…' (War Office 1921, p. 65; 1925, p. 73).

With the possibility of troops standing in cold water in undrained or water-logged trenches, came the probability of 'trench feet', a condition that directly affected the effectiveness of the fighting forces. Field Marshal Sir John French, commanding the British Expeditionary Force, estimated casualties from 'Trench Feet' to be somewhere in the region of 20 000 men in the winter of 1914–1915 (French 1919, pp. 288–289). As such, by 1916, the advice of the *Notes for Infantry Officers on Trench Warfare* (Lake 1916) was that drains of 'adequate capacity' should be engineered into the floor of the trench as it was being built, sturdy and 'boxed in' to prevent collapse.

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As had been suggested by Walter Kranz, drainage of field fortifications was intended to present a major task for engineers and their geological advisors. The German manual, *Stellungsbau*, noted sagely 'If the water level in the country is high, special measures to deal with it may be necessary' (General Staff 1917*c*, p. 6). In this respect, the German army became expert in the drainage of trenches as the war progressed. This expertise was recognised by their enemies, the British:

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> Great attention is paid to drainage of trenches, as on the success or non-success of the measures taken may depend whether this position can or cannot be held in the wet season. It is laid down that the drainage must be done on a definite plan which must be carried out in good time. Drainage engineers and geologists are to be consulted, and use made of existing maps and plans. Wherever possible, the drainage water is to be led in the direction

of the enemy, pipes being put through the parapet for this purpose (General Staff 1917*c*, p. 6).

Case Histories

Examination of trenches in archaeological investigations in France and Belgium over the past 25 years provides the means of testing the application of the military manuals in practice, and of examining the details of military engineering geology on the ground, particularly with regard to slope stability and drainage. Four excavations are discussed here, three in the viscinity of the Belgian city of Ypres (Ieper), in Flanders, and one in Picardy, France, on the Somme battlefield.

Boesinghe (Ypres), Belgium

The entrenchments at Boesinghe comprise both trenches and deep mined dugouts. The trench/dugout system is located close to the Yser Canal to the north of Ypres, close to the end of the British line (Fig. 10).

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These British trenches were constructed in late 1915, after the German offensive of spring 1915. At this stage in the war the system of trenches was constructed with standard front, support and reserve lines, connected by communication trenches. In 1992 the area was being cleared as part of the development for an industrial park north of the prosperous city of Ypres. During these works, a trench system was uncovered with an associated deep mined dug-out; this had a maximum depth of approximately 10 m, and is thought to have been constructed by the 173rd Tunnelling Company (RE). This dug-out served as the headquarters of the 13th and 16th Royal Welsh Fusiliers in the Third Battle of Ypres (Saunders 2011). Development proceeded while local amateur archaeologists excavated the site, which was associated with both the Second and Third Battles of Ypres, in 1915 and subsequently, in 1917. Part of the site is now preserved in concrete (Saunders 2011).

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The trench system exposed by the 1992 excavations was shallow; it had been developed in a thin layer (up to 2.2 m thick, according to the contemporary geological maps) of Quaternary soils, sands and silty clays that overlie the Ypres Clay plain. Situated ~~west~~ east of the Yser canal, cut deeply into the Ypres Clay, the British line had the canal to the rear, its embankment raised up from the clay forming a significant position for the construction of dug-outs and other shelters. The trench line lies on approximately the 15 m contour line, and faced a German line that sits close to the 20 m contour, the westwards extension of the Pilkem Ridge. The difference in heights also represents differences in geology—the Germans squarely upon the sands that sit on the clay (Kortrij~~y~~k Formation), the British at its feather-edge. Comparison with the most modern geological map, published by the Belgian Geological Survey (1999) shows correspondence of the old front line with the junction between the Ypres Clay (Kortrijk Formation) and the Paniselian sands (Tielt Formation).

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Here, a German strong point, the Caesar's Nose, pushed westwards towards the British line using a low-lying spur as its point of reference. This work had, in fact been part of a contested system of trenches, with both sides effectively sharing the line in 1915 (MacGreal 2011). The 6th West Yorkshire Regiment arrived in the line in July 1916, and found it to be dry, though these conditions were not to last.

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> When the battalion first took over the line, the trenches had not fallen in. The precautions which began to be adopted on a big scale in 1916 to preserve trenches from collapsing in the winter months (such as A frames and other systems of reveting) had not been taken in the Salient. The Division [49th] arrived too late to organ~~ise~~ize draining and reveting on a sufficiently elaborate basis. The result was disastrous. When the Autumn rains began in August, the trenches disappeared, or became canals… The line could only be held by a system of detached posts, where men were prisoned till nightfall, up to the knees in water day and night… Tremendous efforts were made throughout the Division to combat the most serious danger of water-logged trenches—'trench feet'… (Tempest 1921, p. 50).

The trench system had to be considerably improved, in line with the advice provided by *Notes on Trench Warfare for infantry Officers*, and in particular the use of A-frames as illustrated in its revised diagrams (General Staff 1917*a*, fig. 13; see Fig. 7). By mid 1916, these A-frames were in use—Lieutenant Grover of the King's Shropshire Light Infantry recalled their function in this sector:

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> I spend a lot of time in the Salient, where the water level is just below the surface, and when it rains the whole thing is just one field of mud, so all the defences have to be built up. Which means you not only have to build them up with sandbags, you have to revet them very strongly. We had things called 'A Frames', in the form of an inverted A with a trace across to allow a drain below, and that was the inside of the trench, these were fitted in and were reveted inside (MacGreal 2011, pp. 109–110).

These trenches were therefore constructed using breastworks, and the archaeological work demonstrated the presence of the inverted 'A' frame structures: intended to support the revetments and breastworks of sandbags, and to ensure that there was an engineered solution to the maintenance of over-steepened slopes (Figs 7 and, 11a,b). Examining the site carefully, it is possible to see that the trenches themselves were about a metre in depth to the duckboard surface, with up to another metre beneath this to the level of water saturation. This is consistent with a position for the trench, just overlying the impervious Ypres Clay. Other, more simply constructed trenches, earlier versions, were also found in this area. In at least one part of the trench the presence of several successive layers of duck-boarding suggests attempts to raise trench floor level above the saturated ground before the A-frames were installed.

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Messines, Ypres, Belgium

If the trenches at Boesinghe were typical of British trench architecture of 1915–1917, comparison with German lines would be instructive. German front-line trenches at Messines at the southern extremity of the Ypres Salient (south of St.

Eloi) were excavated in 2012–2013 as part of a major replacement of water mains in the region (Verdegem *et al.* 2013).

The excavation site uncovered a German trench system that was located on the slopes of the Messines Ridge, just above the valley of the Douve, surrounding the town of Messines itself. Messines sits on a spur of the main ridge system east of Ypres, and forms part of wider plateau with Wytschaete to the northwest, and Messines to the south (Fig. 12). This plateau had seen hard fighting in 1914, and had stabil~~ise~~ized in its position in 1915, becoming a dominant fortress, comprising a system of strongpoints that were designed to break up any attempt to take the ridge top by frontal assault. With the Germans occupying the high ground, with every spur and building built into the line as a fortress (in line with the doctrine laid down in the German manual, *Stellungsbau* (General Staff 1917*c*, p. 3), the British were forced to build trenches that were effectively 10 m lower, facing the forward slopes of the ridge (Doyle *et al*. 2002).

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C~~C~~apping the ridge top at Wytschaete are the driest sands, known to the British (not surprisingly) as the 'Wytschaete Sands' (Fig. 13; s~~S~~ee Rose & Rosenbaum 2011, tables 2 and 3). The recent map (Belgian Geological Survey 1999) has this as the Gent Formation, situated just to the west of the village. Messines is built on the Tielt Formation—the sands and clays of what was called the Paniselian. But for the most part, the rest of the ridge is composed of the various levels of the 'Paniselian', overlying, as always, the Ypres Clay. Here are found the water-logged 'Kemmel Sands', sandwiched between the clay-rich layers, and there were even wetter 'alluvial' soils, that thicken to considerable depth in the valley of the Douve at the foot of the ridge (see Rose & Rosenbaum 2011). ~~To the west, in the distance, was the British-held high point of Mont Kemmel, with the valleys of the Steenbeek (flowing to the south) and Haringbeek (flowing to the north) between them—again filled with wet alluvial soils.~~

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The trench system was constructed as a strongpoint in the German front line. ~~In fact the excavations disturbed what was the German second line in the defensive system constructed here.~~ In the excavation trenches cut by the archaeologists

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were exposed in turn the details of the German Great War trenches, incredibly well preserved. Here was *Eckert-Graben* (known as 'Uhlan Support' to the British) a second line position organ~~ise~~ized as a firetrench; a machine-gun position; and a communication trench, *Blauer Graben.* To the south of Messines, on the slopes facing the Douve, was exposed *Emil Graben* ('Uhlan Avenue') a line to the rear of the Second line (Verdegem *et al*. 2013, p. 104). The German lines here almost exactly follow the junction of the Kemmel Sands, between the 50 and 60 m contours. While the centre of Messines sits on drier ground, the trenches constructed in front of the village sit squarely within the outcrop of the water-rich Kemmel Sands, and once again there was the threat of flooding from the ever-present impervious clay beneath, as seen in the contempoary geological maps constructed by the British in 1917 (1:10 000 Map Geological, Ploegsteert, 28SW4, May 1918. The National Archives file WO297/2475; see Rose *&* Rosenbaum 2011). Not only that, but the valley of the Douve was filled with water-rich alluvium, sediments that had been built up by the flow and overflow of the river in a subsiding valley to an extent that it was *c*.30 m thick at its deepest (see Fig. 13; beneath the location known as Ontario Farm). This wet ground caused problems for the tunnelling companies that were trying to undermine the German defences here (see Barton *et al*. 2004; Doyle 2012). It also meant that as the British and German trench lines breasted the ridge and moved down into the valley on to Ploegsteert and beyond, there was increasingly difficult, wet and water-logged conditions for both sides (Brown & Osgood 2009).

Evidence of periodic flooding from the sands is provided by successive layers and levels of timber flooring and duckboarding—this is not surprising given the geological situation here. On top of the typical long trench boards are timbers laid so that they resemble duck boards of the British type. It is probable that these trenches were drained using the German system, on the basis that wherever possible, the fall of drainage should be towards the enemy. This approach was facilitated by the simple fact that the German lines lay on the slope above the British.

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Exposed in the archaeological investigations at Messines were narrow trenches that were boarded throughout, and that were reveted with a variety of means (Fig. 14~~2~~). This included the rescue of doors and other timbers from damaged and destroyed buildings in the village. Timber used in trenches in this way was potentially dangerous—it could provide splinters that would add to the problems of men tightly packed in the line. Also *in situ* is the brushwood hurdling that is commonly seen in German trenches. This type of revetment was the preferred means of protection—but was difficult to replace in the shell-blasted landscape of Flanders. The manual *Stellungsbau* was clear on this point:

> The sides of trenches must not be reveted with any material that may make traffic in the trench impossible or even difficult after bombardment. Planks and timber should not be used if possible. Hurdles are not so objectionable. The best reveting material is sods or thin loose brushwood (General Staff 1917*c*, p. 15)

Here and there the revetment shows the impact of British shelling with extreme disturbance to the timbers of the German line. Such revetment was held in place by vertical members, some of them cut branches rather than shaped timber, and the trenches are uniformly cut through the water-rich silts and sands of the Paniselian.

The German trench system also included a concrete shelter with room for six or seven men, located at the termination of *Eckert Graben* (Fig. 15~~3~~). This was cast *in situ*, and must have been a response to the damp conditions. The water-rich sands, into which the trenches were dug, meant that concrete was the solution to providing shell-proof shelters, rather than deep dug-outs. This concrete shelter gave access to the Second Line, through a reveted and planked trench, and was fully equipped with an internal pump. From its entrance was a carefully prepared rifle rack and a recess with hinged lid that contained German stick-grenades, found as they had been left by the last German occupants in June 1917.

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Four shallow mined tunnels were also uncovered in the excavations (Verdegem *et al*. 2013, p. 150). At a depth of just 2–3 m, the protection given to them from howitzer shells was likely to have been limited headcover, though it appears that there is a rubble 'burster course' of building waste, suggesting that the tunnels were constructed as 'cut-and-cover'. Each tunnel was constructed using a 'mining case' timber revetment, supported by bridle joints and pegs. Most likely the purpose of these tunnels was for storage and concealment, rather than protection from artillery bombardment. The tunnels have no inclines—just simple adit entrances from the trench line to the south of Messines. The tunnels sit between the 45 and 50 m contours, in Paniselian sandy-clays that underly the difficult and water logged 'Kemmel Sands' (geological detail from 1:10 000 map, Geological Ploegsteert 28 SW4, The National Archives file WO297/2475)—a factor that suggests that, in winter at least, these tunnels had to be drained effectively, either by drains running downslope or by pumping.

La Boisselle, Picardy, France

In Picardy the opportunity to observe excavated trenches has been provided by research at La Boisselle on the Somme battlefield (Fig. 16~~4~~). Here, in 2011–2012, one of the last remaining pieces of original extant battle terrain on the Somme battlefield was excavated by the La Boisselle Study Group (see www.laboisselleproject.com for details). Situated in the village of La Boisselle, the terrain captures a snapshot of the Allied (British) and German frontline trenches dug into chalk from the period 1914–1916. Here, at a farm known to the French as 'Ilôt' and the Germans 'Granathof', the French stopped the German advance on the Somme on 14 September 1914. With the village firmly held by the Germans, this part of the frontline was exploited by underground warfare, with numerous attempts to dislodge the enemy using mines, commencing in December 1914 and continuing until the British took over the front line in August 1915. From this point on the British took over the tunnelling activity, deepening the system from around 12 m to 24–30 m below ground. These mines,

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forming craters at the surface, formed part of 'No Man's Land'—just 45 m apart—up to the opening days of the Battle of the Somme.

The nature of these very trenches were recorded by Charles Douie, a British officer who served in them in 1916:

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> I learned something of the reputation of the La Boisselle trenches. They were among the most notorious in the British lines. For a considerable distance the opposing lines were divided only by the breadth of the mine craters: the British posts lay in the lips of the craters protected by thin layers of sandbags and within bombing distance of the German posts; the approaches to the posts were shallow and waterlogged trenches below the level of the German lines, and therefore under continuous observation and accurate fire by snipers (Douie 1929, pp. 87–88).

With No Man's Land so challenging, and with the need to maintain the offensive, mining activity here was extensive—and had been so since late 1914 (Simon Jones, pers. comm.). La Boisselle was captured by the British on 4 July 1916, and the notorious trench system and its mines were left behind.

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The trenches excavated by the La Boisselle Study Group expose a small system facing the mine craters and supporting a number of adits that lead underground (War Diary 53 Infantry Brigade, Headquarters: The National Archives file WO95/2033). As described by Charles Douie, the trenches were relatively shallow here, dug directly into the chalk and therefore directly visible from the air. Here, there are only relatively thin surface soils compared to other parts of the Somme (see Bureau de Recherches Géologiques et Minières 1982); though the chalk is extensively shattered (Fig. 17~~5~~). No doubt some of that shattering could be attributed to the effects of the almost continuous bombardment, but it is more likely that this is a by-product of Quaternary freeze-thaw action and the development of permafrost—which naturally destroyed the integrity of the chalk strata. Lying above this layer is a thin level of soil, consisting of clay or loess with an admixture of chalk blocks, attributed to back-fill and mine spoil by the La

Boisselle Project group. It is likley that these trenches were capable of sustaining relatively steep and therefore regulation slopes, though the frost-shattered chalk would no doubt have required some stabilising revetment from expanded metal or chicken wire.

'Scone Street', one of the main trenches excavated, has access to the extensive underground workings. With weakened chalk for much of its trench slopes, this trench would have required revetment, and there are remains of timber there to support this inference. The level of weak chalk is variable, and at the mid part and base of the trenches there is much stronger, robust, chalk. Flint levels are evident *in situ*—and these would have provided an extra hazard, the brittle flints providing sharp shards if hit by explosives. The presence of the flints shows that the chalk here is from the second of the three main chalk units within the region, of *la craie blanche à silex* (see Bureau de Recherches Géologiques et Minières 1982).

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Given that the clay-rich chalk is at depth, the Tunnelling Companies here found that the water level was at least 100 feet beneath the surface (Simon Jones, pers. comm.)—typical of the chalks at an upper level, at least in summer, with ground waters percolating downwards through the various fractures and levels that character~~ise~~ize the 'block-work' nature of this pure lime rock. It was for this reason that the tunnellers of two specialist Royal Engineer Tunnelling Companies, the 179th and 185th, were able to work below ground to lay their offensive mines. This contrasts with the depiction of 'waterlogged trenches' by Charles Douie—but his experiences surely belong to winter conditions, when the water saturation levels were highest—as well as to local conditions, where the surface soils prevented water drainage.

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Conclusions

From the outset of the war, trench fortifications as deployed by both sides had only ever been intended to be a temporary solution to a military necessity: holding the enemy in a static position until an offensive could be launched, while maintaining the safety of the troops garrisoning them. While trenches were constructed according to the specifications of the field manuals developed for the use of military engineers, in many cases these specifications were undermined by the nature of the geological conditions. Thus, while it was expected that trench slopes would be maintained at over-steepened angles, this was not achievable without sufficient slope engineering and adequate revetment to support the slopes, together with drainage solutions that would reduce the relative ineffectiveness of pumping. Trench systems from 1914–1916 show the construction of breastworks, multiple layers of 'duck-board' tracks and extemporiseized revetments (as in the German lines exposed at Messines). It took a more carefully engineered approach, with the development of 'A' frames, to maintain adequate trench positions in the clay ground ay Ypres (Ieper). That these frames achieved their aim is shown by their continued existence below ground, evidenced by their presence in archaeological investigations near Boesinghe and Wieltje, Ypres. On the Somme, where trenches were developed in the thick Quaternary soils capping the chalk, similar solutions were necessary, though it was possible for trenches to be excavated into the frost-shattered chalk directly, as at La Boisselle, with less need for extensive revetment. These examples illustrate the continuous struggles the armies in France and Flanders had in constructing adequate trench lines, and the development of innovative engineering solutions to weak ground, over-steepened slopes and the persistence of flooding.

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Figure Captions

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Fig. 1. Trace of the Western Front in 1915 (showing the location of British and French offensives of that year). The area of interest in this study is from Nieuport at the Belgian Coast to Albert and the River Somme. (Image: Pubic Domain)

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Fig. 2. Geology of the northern sector of the Western Front. Six broad 'belts' of terrain can be recogn~~ise~~ized from the coast southwards: 1, the coastal dune belt; 2, the 'Polder' plain; 3, the clay Plain of Ypres; 4. The 'sand ridges' to the east and southeast of Ypres; 5, the coal belt of Lens-Bethune; and 6, the chalk of Artois and Picardy. (Image: from Doyle (1998) with permission of the Geologists' Association)

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Fig. 3. Sketch cross section of the geology of the northern sector of the Western Front. ~~(see Fig. 2).~~ The section runs from Arras to Douai, Lille to Ypres, Ypres to Dixmude and the coast (see Fig. 2). (Image: from Doyle (1998) with permission of the Geologists' Association)

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Fig. 4. Ideal~~ise~~ized trench system as developed on the Western Front in 1915–17. (Image: from Doyle (1998) with permission of the Geologists' Association)

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Fig. 5. Sections of atypical fire trench, showing stages of development, and over-steepened slopes or trench sides. (Image: General Staff, 1908)

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Fig. 6. Well-built German trench with brushwood revetment, developed in friable soils *c*.1915–1916. Photograph taken in the summer months. (Image: Public Domain).

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Fig. 7. 'Trench' or 'A' frames introduced to British use in 1916–1917. The inverted A was intended to support the revetment and provide a foundation for duckboard tracks. (Image: General Staff, 1917*a*).

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Fig. 8. In wet ground, usually associated with thin soils on clay, drainage was a problem and an insufficient depth could be developed without superior drainage conditions. In such cases, breastworks were constructed. (Image: General Staff, 1917*a*).

Fig. 9. Problems of drainage in wet trenches in 1914–1915. Pumping was required before more sustainable solutions could be achieved. (Image: Public Domain).

Fig. 10. Location of the Boesinghe trench lines, close to the low ground of the Ypres–Yser canal. The arc of the trench lines is from 1915. Messines is just off the image, south of Hill 60. (Image: Public Domain)

Fig. 11. Trench 'A' frames exposed in archaeological investigations near Ypres (Ieper). (**a**)~~A~~, at Boesinghe, showing the cross of the A, with duckboard track sitting upon it. The trench cuts through Quaternary soils and is floored by clay. ~~B~~(**b**), at Forward Cottage near Wieltje (Fig. 10), showing the engineered slopes maintained in an over-steepened state, with corrugated iron sheeting in position, and once again floored by clay (Images: P. Doyle)

Fig. 12. Map of the Ypres (Ieper) Salient, 1915–1917, showing the location of Messines, and the British front line at the start and end of the Battle of Messines in 1917. (Image: from Doyle (1998) with permission of the Geologists' Association)

Fig. 13. Geological section north–south through theWytschaete–Messines ridge,showing the location of the'Kemmel Sands' towards the top of the ridge, and the use of the lower levels of the 'Paniselian' for the construction of the British mine galleries used in the Battle of Messines, in June 1917. (Image: from Doyle (1998) with permission of the Geologists' Association)

Fig. 14~~2~~. German frontline positions at Messines. Situated close to the Kemmel Sands, there was constant flooding, evidenced by successive levels of duckboarding. Here, inadequate revetment is provided by timbers salvaged from destroyed buildings (Image: P. Doyle).

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Fig. 15~~3~~. German solution to flooding and inadequate revetment in the frontline trenches at Messines: a concrete shelter cast in situ. (Image: P. Doyle).

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Fig. 16~~4~~. Map of the Somme Battlefield, showing the location of La Boisselle. The chalk is exposed at the surface here, though much of the Somme is blanketed by Quaternary deposits. (Image: from Doyle (1998) with permission of the Geologists' Association)

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Fig. 17~~5~~. 'Scone Street', one of the frontline trenches cut in chalk at La Boisselle. Here, there is direct access to the chalk, with a very limited Quaternary cover. Trenches are more capable of sustaining steep slopes, though the frost-shattered chalk often required chicken-wire netting support. (Image: P. Doyle).

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Figure 1

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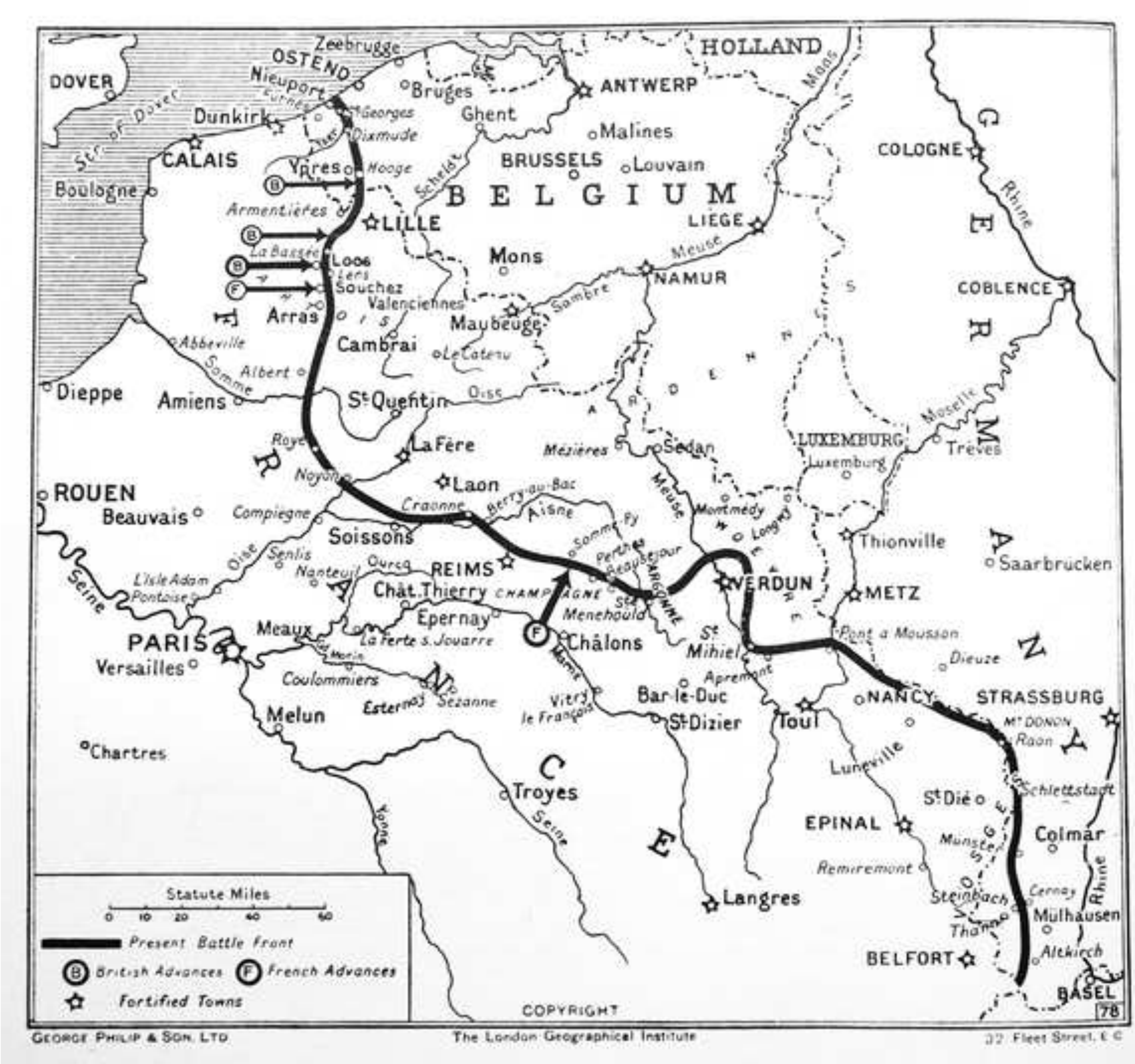

Figure 2

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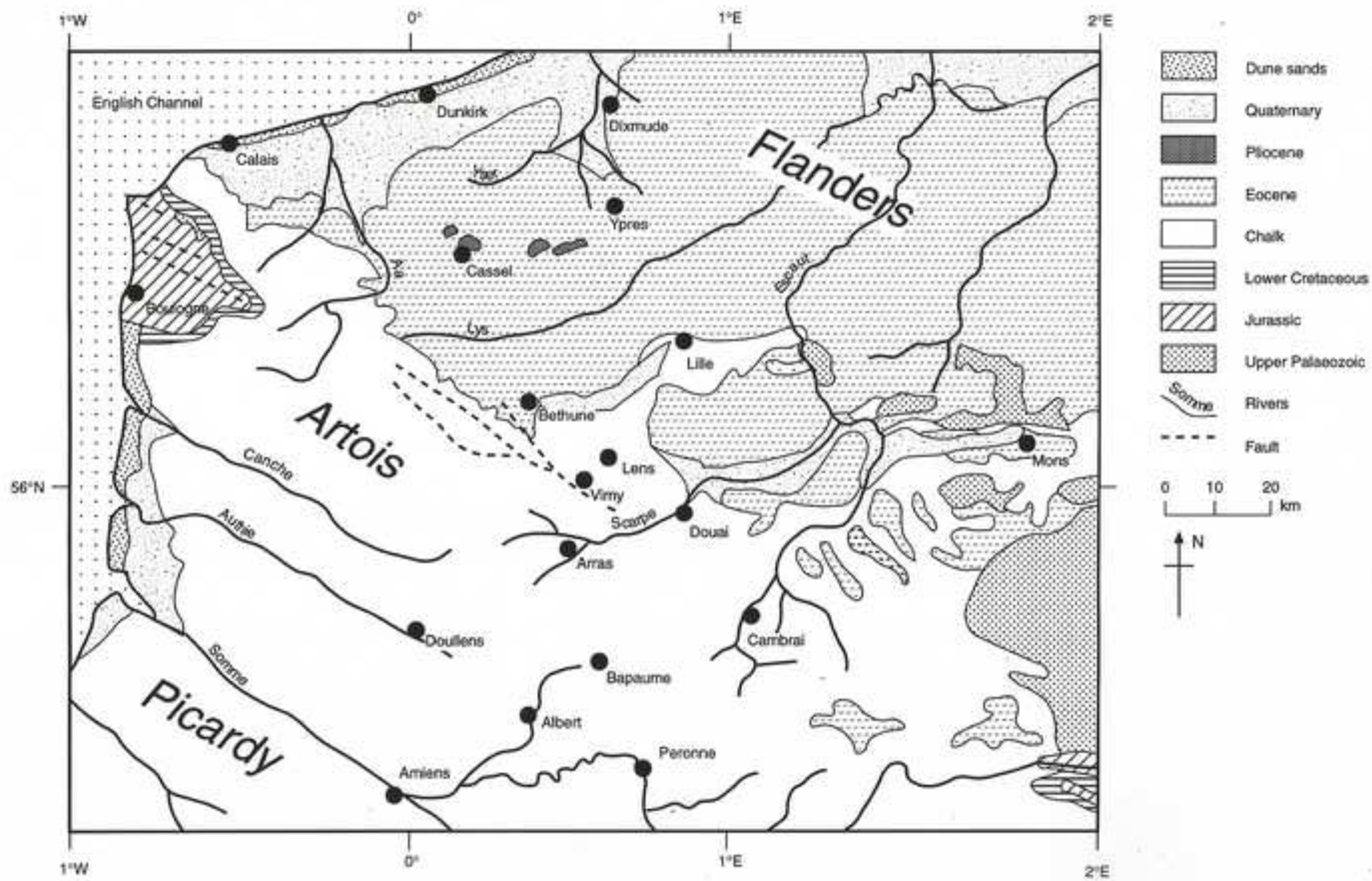

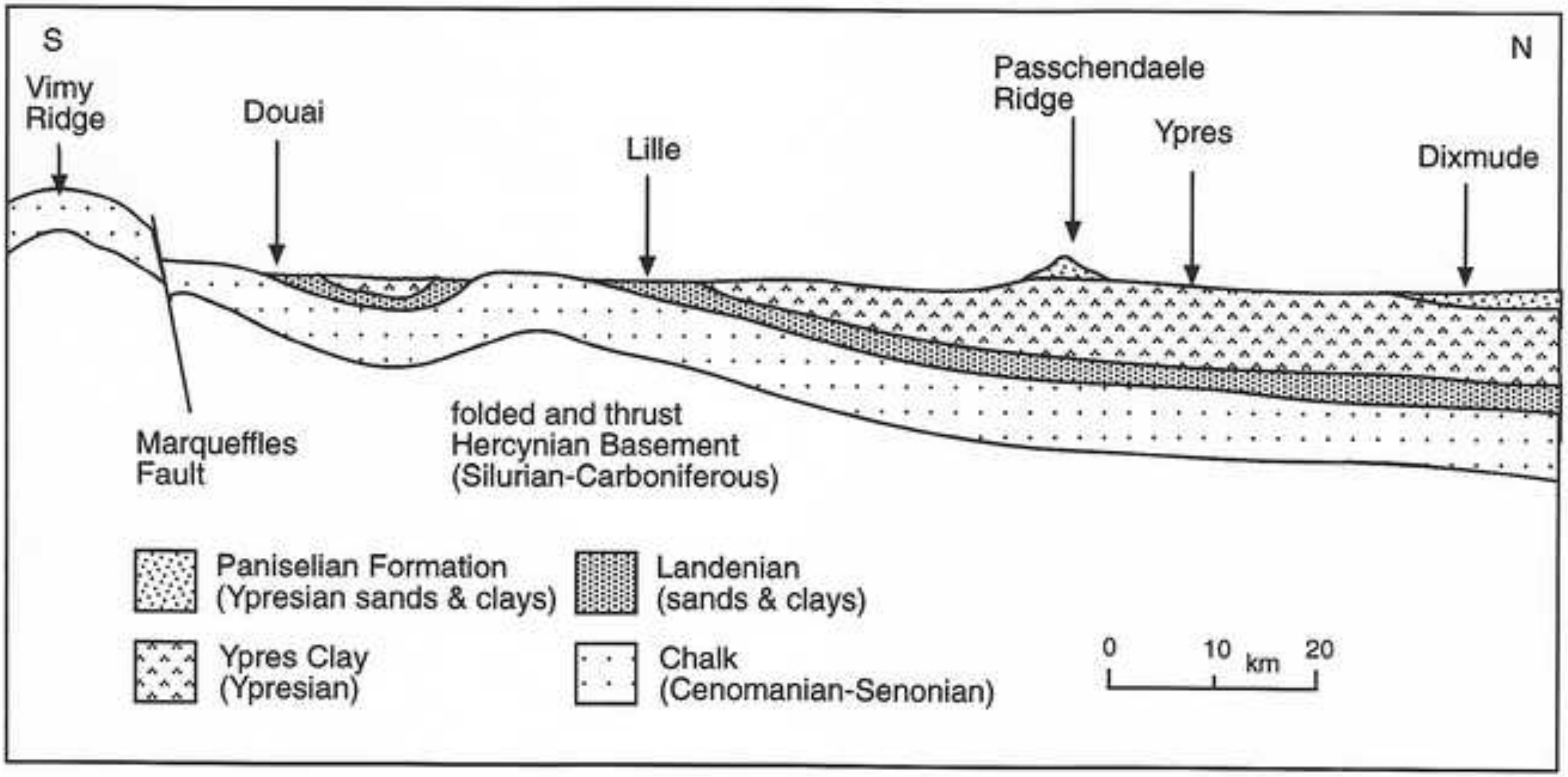
S
N
Vimy Ridge
Douai
Lille
Passchendaele Ridge
Ypres
Dixmude
Marqueffles Fault
folded and thrust Hercynian Basement (Silurian-Carboniferous)
Paniselian Formation (Ypresian sands & clays)
Landenian (sands & clays)
Ypres Clay (Ypresian)
Chalk (Cenomanian-Senonian)
0
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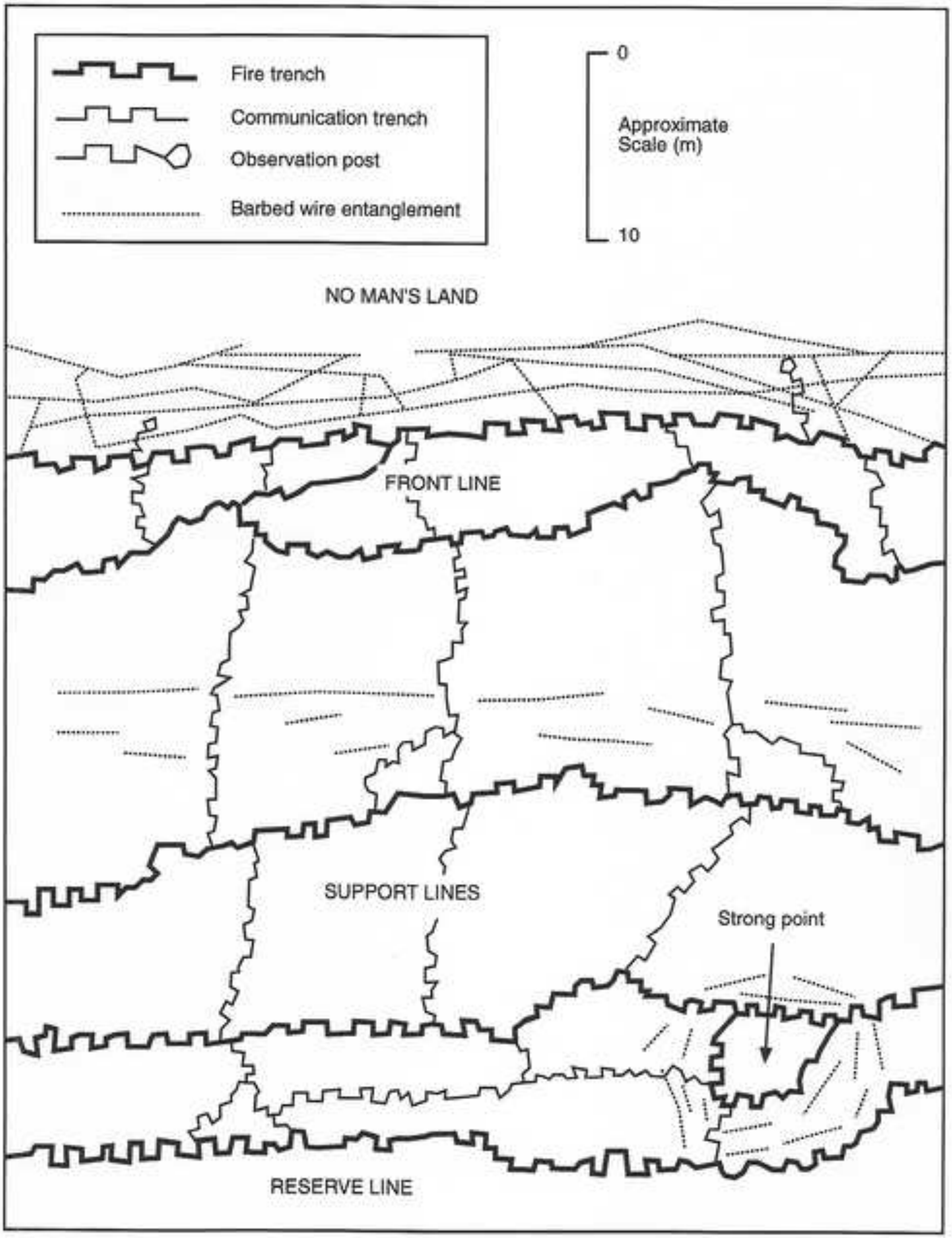

Figure 5

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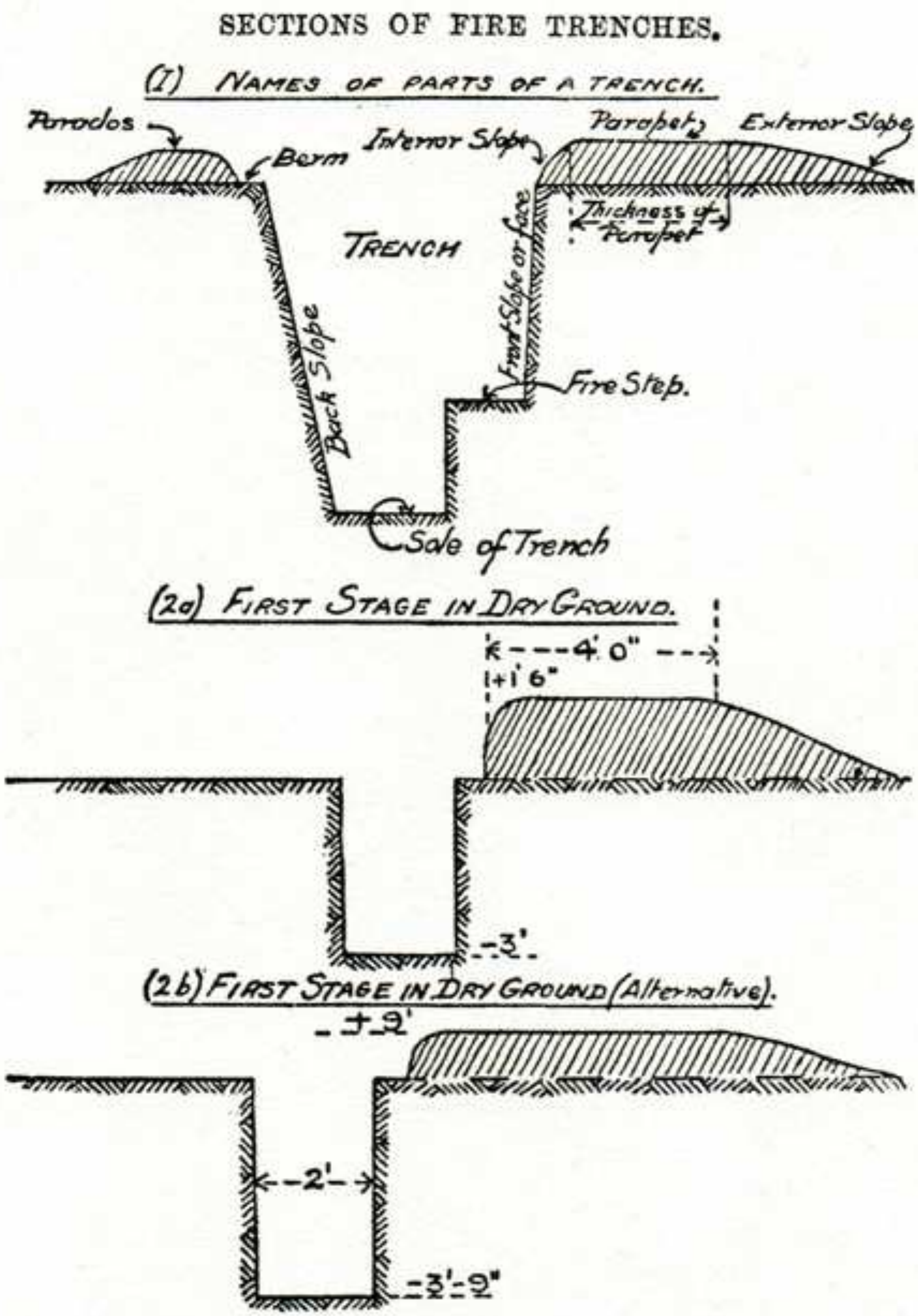

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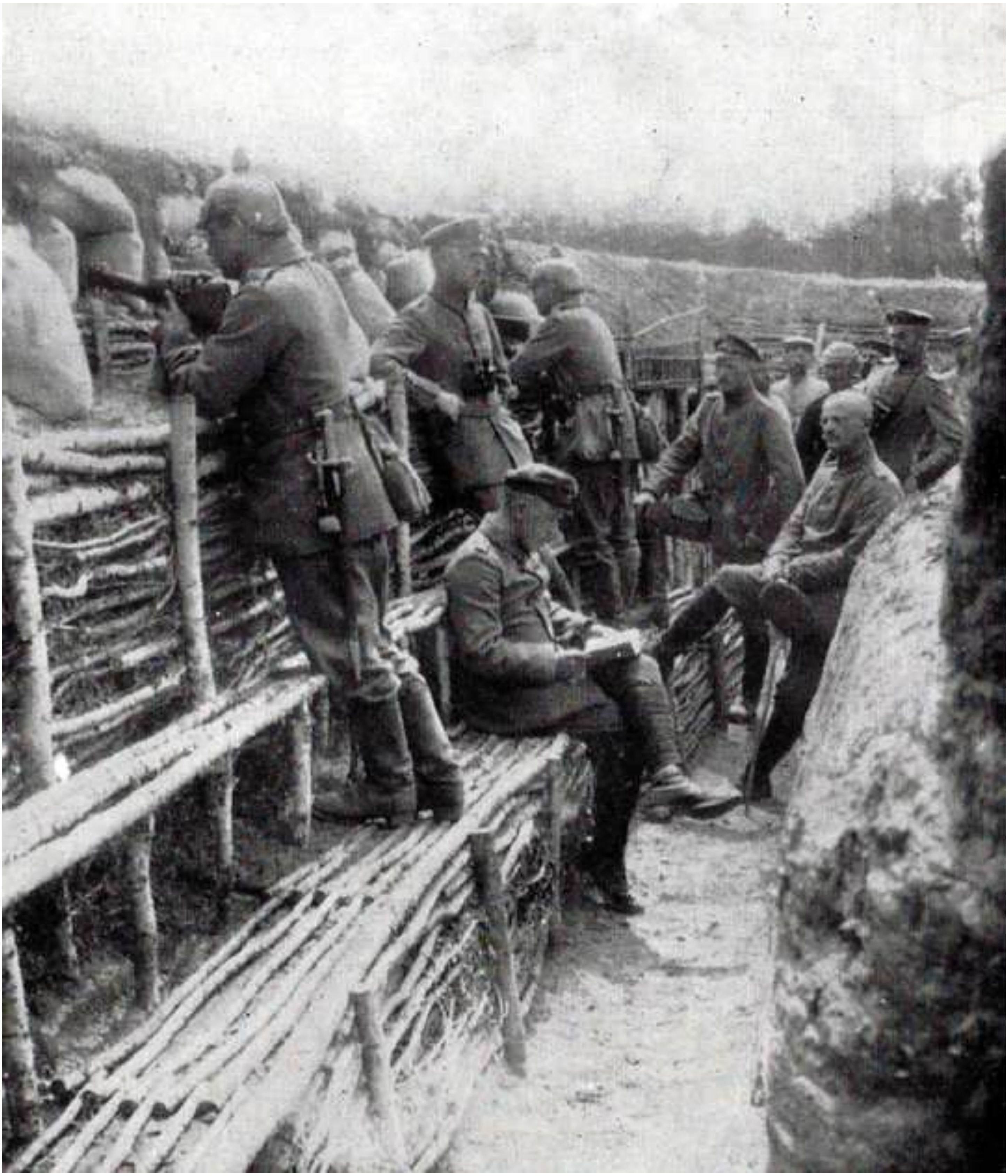

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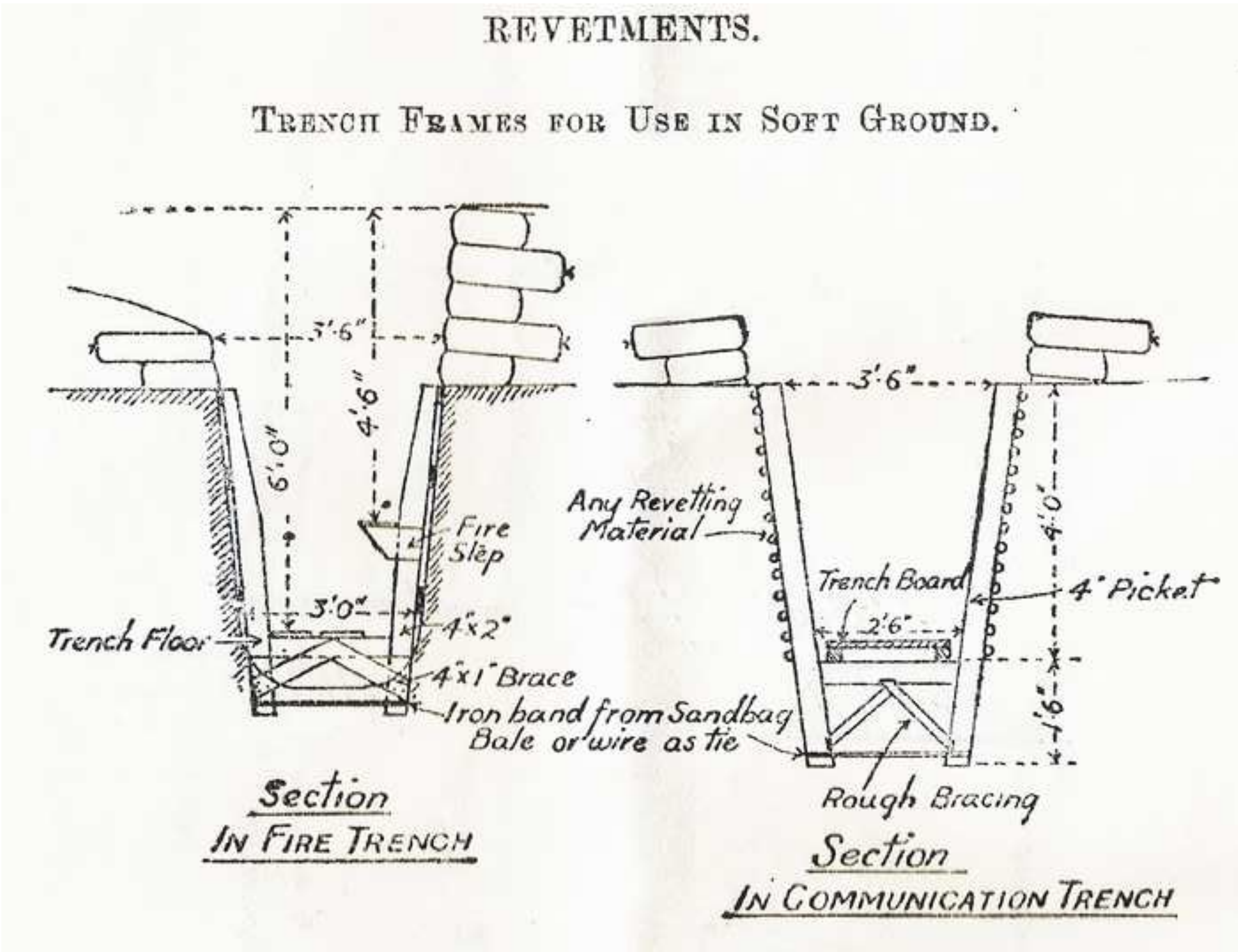
REVETMENTS.
TRENCH FRAMES FOR USE IN SOFT GROUND.
3'6"
4'6"
6'0"
Fire Step
3'0"
4"x2"
Trench Floor
4"x1" Brace
Iron band from Sandbag Bale or wire as tie
Section
IN FIRE TRENCH
3'6"
Any Revetting Material
Trench Board
4" Picket
2'6"
4'0"
1'6"
Rough Bracing
Section
IN COMMUNICATION TRENCH

Figure 8

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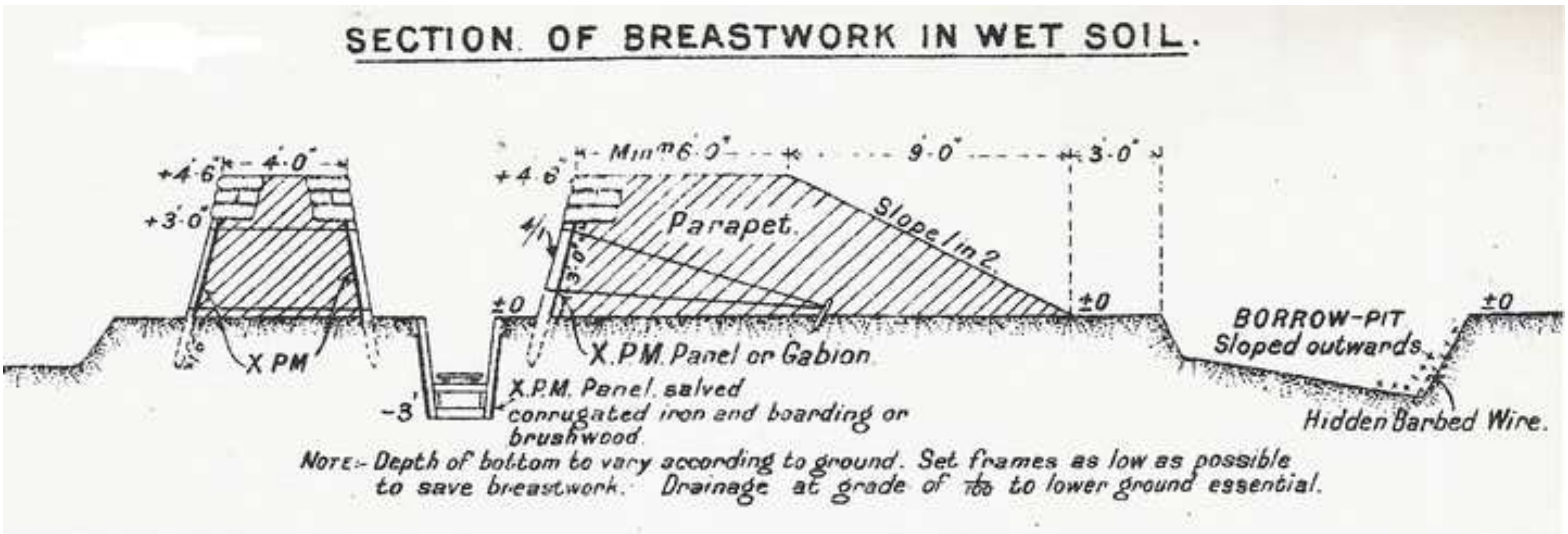

Figure 9

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Figure 10

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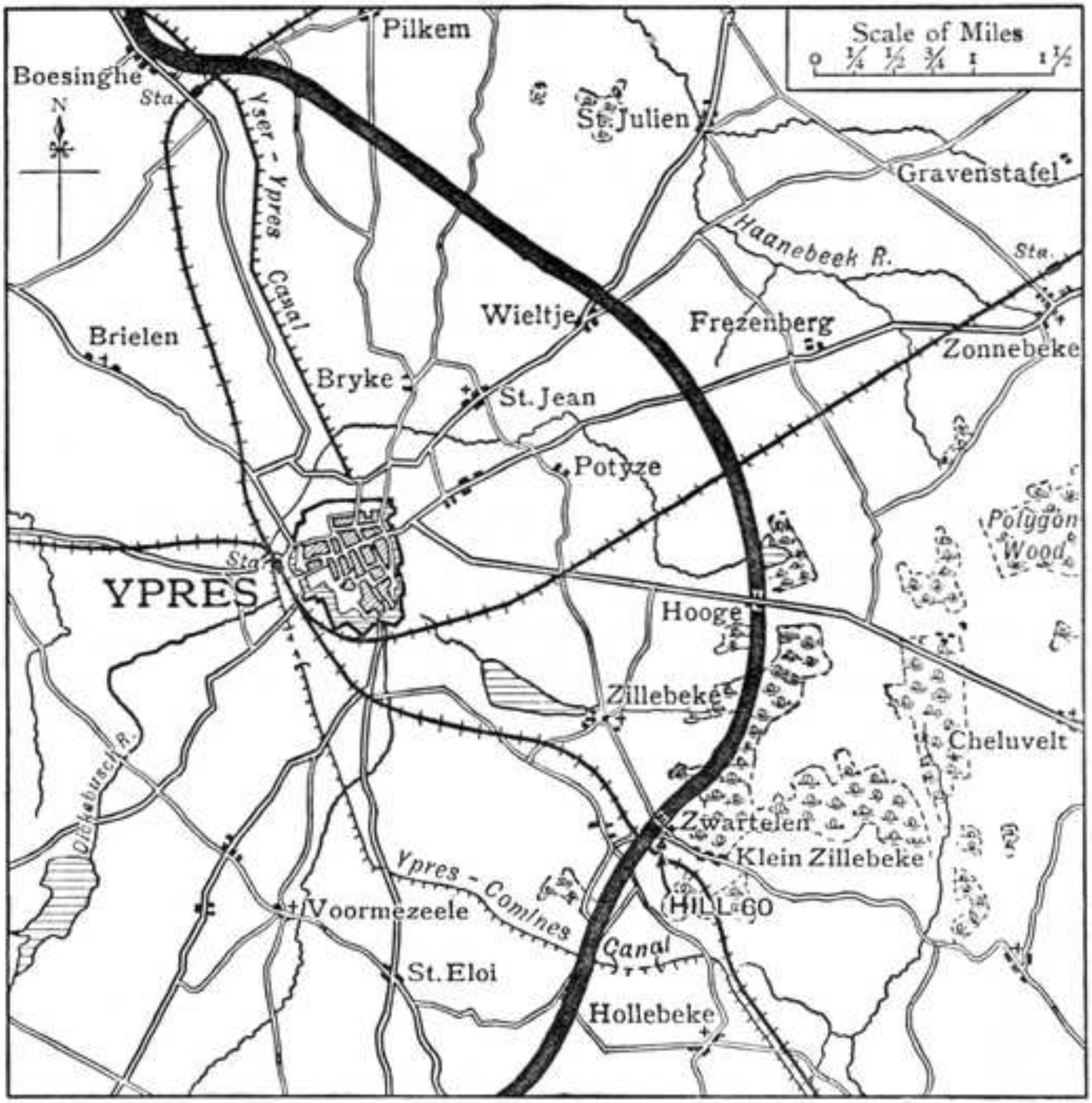

Figure 11a

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Figure 11b

Figure 12

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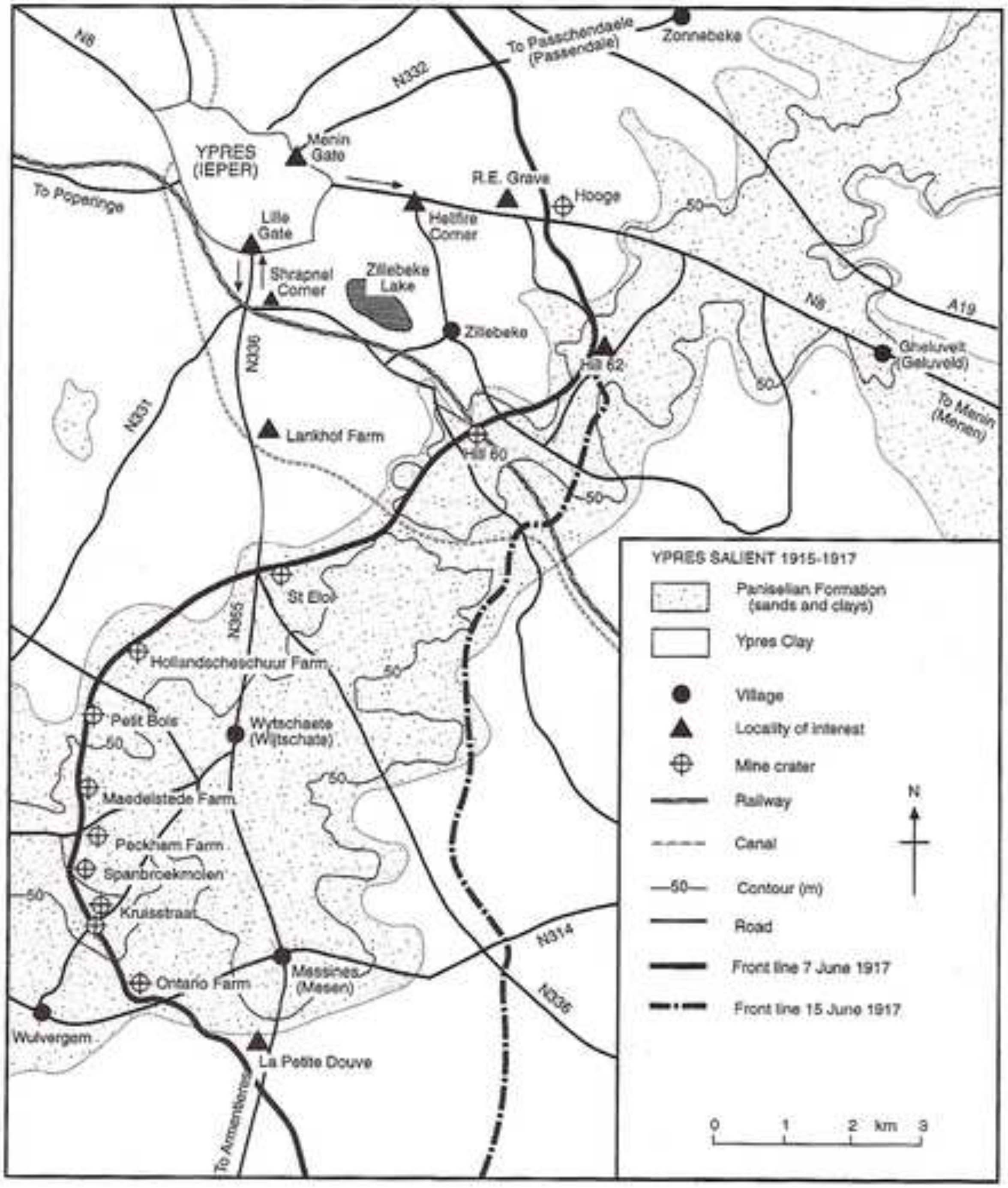

Figure 13

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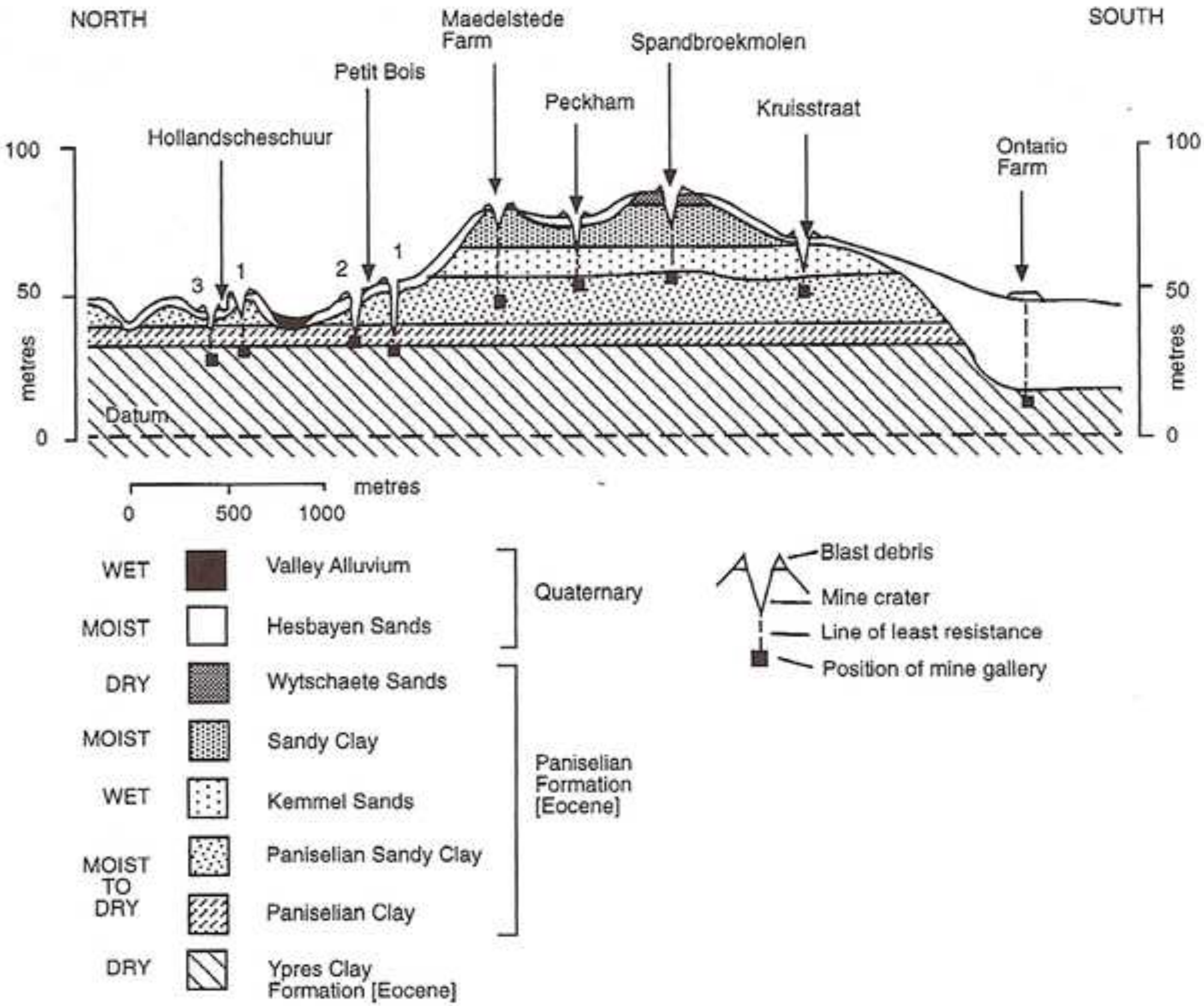

Figure 14

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Figure 15

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Figure 16

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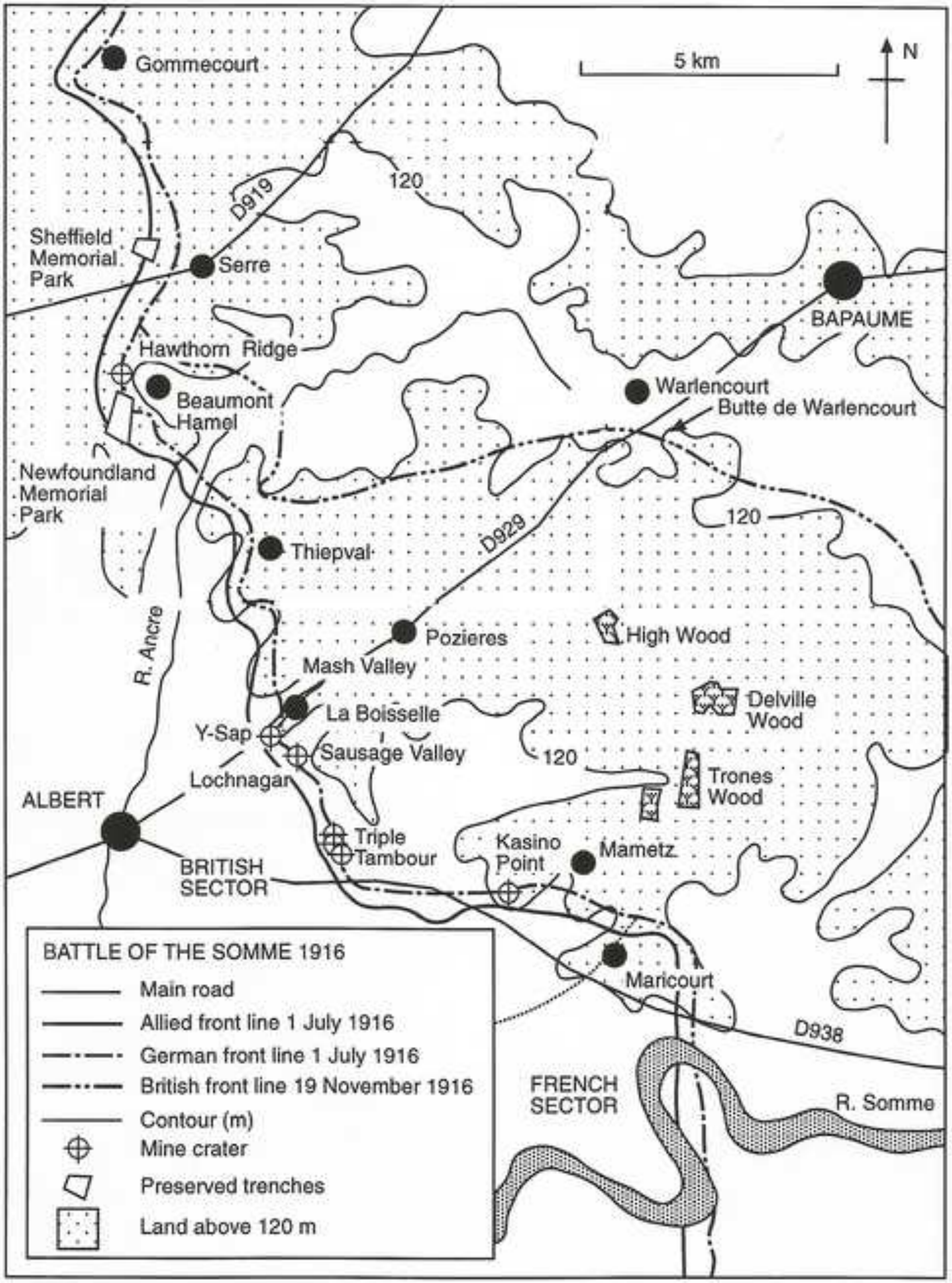

Figure 17

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