Military use of geologists and geology: a historical overview and introduction

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Abstract: Napoleon Bonaparte was, in 1798, the first general to include geologists as such on a military operation. Within the UK, the following century saw geology taught, and national geological mapping initiated, as a military science. Nevertheless, military geologists were not deployed on a battlefield until World War I, first by the German and Austro-Hungarian armies and later and less intensively those of the UK and USA. Geologists were used primarily to guide abstraction of groundwater, construction of ‘mine’ tunnels and dug-outs, development of fortifications and quarrying of natural resources to enhance or repair supply routes. Only the USSR and Germany entered World War II with organized military geological expertise, but the UK and later the USA made significant use of military geologists, albeit far fewer than the c. 400 in total used by German forces. Military geologist roles in World War II included most of those of World War I, but were extended to other aspects of terrain evaluation, notably the rapid construction of temporary airfields and factors affecting cross-country vehicular movement (‘going’). After 1945, more military geologists were used in the USA than Germany or the UK, in these and wider roles, but mostly as civilians or reservists.

Although there had been an association between military men, mineralogy and mining in parts of Europe from at least the mid-eighteenth century, military applications of geology as such became apparent only from Napoleonic times onwards (Rose 2009a). During the nineteenth century, at least within the UK, geology itself was initially perceived to be a military science. This perception had lapsed by the end of the century, but the Great War of 1914–18 saw ‘military geology’ developed as a new discipline within geoscience. Stimulated by the two World Wars and succeeding Cold War of the twentieth century, similar applications of military geology were rapidly developed in parallel, but mostly independently, by the armed forces of the opposing nations. This article provides a historical account from the Napoleonic origins of the discipline to the present day as the foundation for an introduction to the papers that comprise the rest of the volume.

A benchmark book on military geology (Underwood & Guth 1998), the first to be published following the end of the Cold War of 1947–91, was introduced by George Kiersch, a distinguished American engineering geologist and former World War II military engineer. His historical overview (Kiersch & Underwood 1998) reflected understanding of the subject in the USA at that time and was also published, in extended form, as a journal article (Kiersch 1998). The book was generated by a symposium that became the first in a series of meetings now entitled the International Conferences on Military Geosciences. These meetings take place near-biennially and alternated between the USA and Europe until the twelfth, which was held in South Africa in 2017 (Rose 2018a). Data from other books generated by the early conferences (Rose & Nathanael 2000; Ehlen & Harmon 2001; Doyle & Bennett 2002; Caldwell et al. 2004) helped an encyclopedia summary by Rose (2004a) to be extended
into a historical overview to complement those by Kiersch by adding a European perspective (Rose 2008a). The present article enhances previous overviews with data from books generated by subsequent conferences (Nathanail et al. 2008; Häusler & Mang 2011; McDonald & Bullard 2016) plus other recent books (Rose & Mather 2012; Harmon et al. 2014) and ten more years of ancillary published research.

Nineteenth-century foundations

For the nineteenth century, significant perceptions of military applications of geology can be demonstrated from France, the German-speaking states of mainland Europe and, most importantly, the UK. Relevant literature from other countries is relatively sparse, but an article in Spanish that was translated into French (Quijano y Arroquia 1876) is evidence of wider European interest.

Napoleonic France

Napoleon Bonaparte was the first general to take geologists as such on a military expedition, when he led a French invasion of Egypt in July 1798 (Rose 2004b, 2005a, 2008b). His army was accompanied by a Commission of Sciences and Arts, c. 150 engineers and other technical experts whose task was to examine almost every aspect of ancient and contemporary Egypt so as to enable the French to occupy and govern the country effectively. Four members of the Commission were listed as ‘minéralogistes’ (geologists): Déodat de Dolomieu together with three of his former pupils at the School of Mines then being redeveloped in Paris, Louis Cordier, François-Michel de Rozière and Victor Dupuy (alias Dupuis).

Dolomieu (Fig. 1), from whom the mineral dolomite is named and consequently the Dolomite mountain range of NE Italy, was one of the four most senior members of the Commission. An aristocrat with distinguished geological achievements to his credit, his initial career within the Sovereign Military Order of Malta had ended as a consequence of the French revolution of 1789. Following seizure of his family estates and suppression of the Order in France, he had gained employment as an inspector of mines and a visiting professor of geology at the nascent School of Mines in Paris. He had volunteered to join the expeditionary force to Egypt through love of adventure and the chance to explore a relatively unknown country, gaining a place through his status at the School of Mines and friendship with other senior members of the Commission. However, illness forced him to leave Egypt in March 1799, before the French army had gained access to the country as a whole and much geological work had been done.

Cordier left Egypt to accompany Dolomieu on his homeward journey. He subsequently developed a distinguished career in the French government’s Corps des Mines and as a Professor of Geology at the Natural History Museum in Paris. Rozière and Dupuy remained in Egypt until the French army was defeated and expelled by a British expeditionary force in 1801. Both returned to France and to careers in the Corps des Mines, Rozière, from 1820 to 1824, concurrently as Professor of Geology and Mineralogy at the Saint-Étienne School of Mines, near Lyon. He was almost entirely responsible for publication of French geological achievements in Egypt, but these featured pure rather than applied aspects of geology and made no contribution to military geology as such.

Napoleon returned to France in late 1799 to seize power as First Consul and in 1804 to change the Republic into an Empire, with himself as Emperor. The French Revolutionary Wars of 1792–1802 continued from 1803 as the Napoleonic Wars. From
1792 until 1815 conflict blazed at times across almost the whole of Europe, from Portugal in the west across Spain, France and central Europe into Russia in the east, and extended into Africa, North America and the Far East (most notably India). Although Napoleon himself made no use of geology or geologists in his campaigns after Egypt, even for his final battle, at Waterloo in Belgium, in 1815 (Rose 2015a), a precedent had been set. Scientific investigations made in connection with military expeditions were adopted by many nations in the following century. Much of the early knowledge of the western USA was gained in this manner (Betz 1984).

German-speaking European states

Karl Georg von Raumer (1783–1865) was one of the geologists in mainland Europe caught up in the Napoleonic Wars (Rose 2005b). A student of Abraham Gottlob Werner (1749–1817) at the prestigious Freiberg Mining Academy in the German state of Saxony from 1805 to 1806, his fieldwork scheduled for 1806 had to be deferred to 1807–08 to avoid Napoleon’s campaigns in Germany. He became Professor of Mineralogy at the University of Breslau in the then Prussian province of Silesia (now part of Poland) in 1811, and volunteered for service with the Prussian army during the 1813–14 war of German liberation from French Napoleonic domination. His knowledge of terrain led to his appointment to the staff of the Prussian General (later Field Marshal) Gebhard Leberecht von Blücher. Some scholars (e.g. Betz 1984; Kiersch 1998; Kiersch & Underwood 1998; Rose et al. 2000) have followed earlier German authors in reporting that Blücher made use of Raumer’s terrain expertise before triumphing over French forces at the second Battle of the Katzbach, on 26 August 1813, and that Raumer should therefore be regarded as a military geologist. However, this seems to have been a misconception (Rose 2005b). Raumer was indeed used as a staff officer during his operational military service, but there is no mention in his autobiography that he made use of geology at this time.

Johann Samuel Gruner (alias von Grouner: Fig. 2) (1766–1824) was, in contrast, arguably the first true military geologist (Häusler & Kohler 2003). A distinguished Swiss mining engineer, he had also studied at Freiberg, taking courses in mining, mineralogy and geology from 1787 to 1790. He later became Director-General of all Swiss mines in the Helvetic Republic, short-lived as a French satellite state. He participated in military operations towards the end of the French Revolutionary Wars, when French troops were campaigning in Switzerland against an Austro-Russian army. He later emigrated to the German state of Bavaria and when, in 1814, Bavaria joined Prussia in the German War of Liberation from Napoleonic domination, he commanded a volunteer rifle battalion in the campaign to drive Napoleon’s army back to Paris. Drawing on his experience both as a geologist and a soldier, he wrote a memorandum in 1820 on the relationship between geology and the science of war, the first such work of its kind, published posthumously (von Grouner 1826). However, the German states were not to be united into a single nation until 1871 and the memorandum made no discernable impact either on geology or military training, in Germany or elsewhere.

It was an Austrian career soldier, Rudolf Freiherr von Schmidburg (1810–1902) who was to draw more significant attention to the relevance of geology to terrain studies and their implications for war, but not until the second half of the nineteenth century (Rose et al. 2000). By the end of the century, military geographers in both France and Italy were also using geology to explain terrain features and land surface conditions (Betz 1984).

The UK

The Geological Society of London, the world’s oldest national geological society, was founded in the midst of the Napoleonic Wars by 11 men dining together on 13 November 1807. Of these, three had military associations (Rose 2009a, 2014). Jacques Louis, Comte de Bourbon, a royalist refugee from...
republican France, was a former Captain of artillery. James Frank had served as a physician with the British Army since 1794, in the higher rank of Inspector of Hospitals since 1800, and with the British expeditionary force in Egypt in 1801. George Bellas Greenough, who became the Society’s founding president, had served part-time since 1804 in the Light Horse Volunteers of London and Westminster, one of the reserve units raised to defend the UK from potential French invasion. However, their interests were in pure rather than applied science, and none is known to have noted potential military applications for geology.

About this time, French wartime domination of Europe prevented importation of limestone pure enough to make the millstones used for grinding gunpowder and its constituents. An explosion in a powder mill was ascribed to use of a substitute limestone containing silica that generated sparks. It was military funding and imperative that consequently initiated geological reconnaissance to find a source of more suitable limestone within the UK. Surveys by John MacCulloch, an employee of the Board of Ordnance which had responsibility for the Royal Artillery and the Royal Engineers, began in 1809 but peace was declared in 1814 before the project came to an end (Rose 1996).

National geological mapping in the UK soon began, under military auspices (Rose 1996). From 1814, MacCulloch received military (Board of Ordnance) funding for geological surveys in Scotland. Funding was transferred to civilian government responsibility in 1826, but the surveys eventually generated a geological map of Scotland, published in 1836. The (Ordnance) Geological Survey of Ireland was founded in 1826 and led until 1828 by Captain J.W. Pringle of the Royal Engineers, a veteran of the Battle of Waterloo (Rose 1999). He was assisted by other Royal Engineers officers: Lieutenants J.E. Portlock, G.F. Bordes, R.S. Fenwick, W. Lancey and A.W. Rode. The Survey was revived in the 1830s under the leadership of Portlock, by then promoted to the rank of Captain. Funding was transferred to civilian auspices in 1845, but the Survey was led by another Royal Engineer, Captain Henry James, until 1846 (Rose 1996). The future British Geological Survey was founded in 1835, again with Ordnance funding, to map initially in England and Wales. It too became a civilian government agency in 1845. By coincidence, the Geological Survey of Great Britain, as it became, was to be led until 1871 by two successive Directors, Henry Thomas De la Beche and Roderick Impey Murchison, who had received military rather than university educations. Murchison, a former infantry officer, was a veteran of the Napoleonic Wars.

During the nineteenth century, geology was among the subjects taught intermittently at all army officer training establishments in the UK (Rose 1997, 2009a, 2014). A course was available from the Professor of Chemistry at the Royal Military College, Sandhurst – the geologist Richard Phillips – for a few years after 1818. Geology was taught at Addiscombe in Surrey to officer cadets of the East India Company’s army, by John MacCulloch from 1819 to 1835 and by D.T. Ansted from 1845 to 1861. For the British Army: James Tennant lectured on geology to Royal Engineer and Royal Artillery cadets at the Royal Military Academy, Woolwich, from 1848 to 1868; T. Rupert Jones to cadets of the infantry and cavalry at the Royal Military College, Sandhurst, from 1858 to 1870; Jones also to young officers of all arms at the Staff College, Camberley, until 1882; and A.H. Green at the School of Military Engineering, Chatham, from c. 1888 to 1896. However, by the end of the century, attempts to teach elements of geology to officers of the British Army in general had largely been abandoned.

By the mid-nineteenth century, military aspects of geology were featuring in publications. A graduate of Addiscombe, Richard Baird Smith, published an ‘Essay on Geology, as a branch of study especially meriting the attention of the Corps of Engineers’ (Smith 1849). Portlock (1849, p. 14), now in the rank of Colonel, published a Rudimentary Treatise on Geology, noting that ‘the Soldier … may find in Geology a valuable guide in tracing his lines both of attack and defence’. He also contributed (Portlock 1850) a 116-page article on geology to the authoritative Aide-Mémoire to the Military Sciences (Lewis et al. 1846–52), a three-volume textbook published for the ‘scientific corps’ of the British and East India Company’s armies. A journal article on the ‘Importance of a knowledge of geology to military men’ was published by Captain F.W. Hutton (1862) on his graduation from the Staff College, Camberley. Increasing awareness of the military relevance of geology can largely be credited, directly or indirectly, to the influence of Joseph Ellison Portlock (1794–1864: Fig. 3). Portlock was a respected veteran, as a combat Royal Engineer officer, of active service in 1812 to defend Canada from invasion by the US Army (Rose 2009a). Later, as already noted, he had helped to found the Geological Survey of Ireland in 1826 and then re-found and led it in the 1830s. His major publications (e.g. Portlock 1849, 1850) had substantial print runs and so presumably high impact on their readers. Retiring with the rank of Major General, he became President of the Geological Society of London for 1856–58. Since Portlock was at that time influential in planning developments in military education, it was presumably no coincidence that a full-time resident lecturer in geology was appointed to the staff of the Royal Military College, Sandhurst, in 1858 and a Professor of Geology at the Staff College after its re-location.
to Camberley nearby soon afterwards, in 1862 (Rose 1997). Both appointments were filled by Thomas Rupert Jones (1819–1911), Assistant Secretary to the Geological Society of London at the time of Portlock’s presidency. Portlock’s own geological expertise assisted military engineering work that included a major fortification programme implemented mid-century in the UK (Mather 2018).

World War I (1914–18)

Military geology as a discipline and military geologists as such were an innovation of World War I, the Great War whose hostilities lasted from August 1914 to November 1918. Most military geologists supported operations on the Western Front, across Belgium and northern France. However, neither the Belgian nor French armies were to include geologists to serve in specialist geotechnical roles. Fighting on their own terrain, their forces were able to draw on civilian expertise in geology as and when required (Hanot et al. 2017; Hubé 2018). The same was true for Russian forces on the Eastern Front (Sychev 1979). Italian forces faced Austro-Hungarian troops in the Dolomite Mountains of NE Italy without the support of a military geological service but were urged to create one post-war (Fossa-Mancini 1926; Fabbi & Romano 2015). Strictly, military geologists were an innovation of the British, American, Austro-Hungarian and especially German armies, and were principally a consequence of the problems caused by large numbers of troops being concentrated into relatively static positions because of extensive trench warfare.

British military geologists

The British Expeditionary Force on the Western Front at its peak consisted of five armies and so c. 1,500,000 troops equipped with c. 500,000 horses and mules, mostly to provide transport of supplies forward from the nearest railheads. Authoritative near-contemporary accounts (King 1919; Anon 1922; Edgeworth David in Rose 2015b) describe how the Force was eventually supported by two military geologists (Fig. 4) based at its General Headquarters, Lieutenant (later Captain) W.B.R. King and Lieutenant-Colonel T.W. Edgeworth David. A third geologist supervised an exploratory boring unit, Lieutenant Loftus Hills (see Rose 2015b, fig. 7).
William Bernard Robinson King (1888–1963) had graduated from the University of Cambridge in 1912 and joined the Geological Survey of Great Britain (Rose & Rosenbaum 1993a; Rose 2015b). He was mapping in the Welsh borderland as war loomed, quickly volunteered for military service and was, on 21 September 1914, commissioned as an infantry officer, a Second Lieutenant in the 7th (Merioneth and Montgomery) Battalion of the Royal Welsh Fusiliers. When the Director of the Geological Survey was asked to nominate a geologist to serve as a ‘water supply officer’ to guide well drilling for the British Expeditionary Force, he nominated King and provided some six weeks of preparatory training in hydrogeology. King moved to France to serve as a Staff Lieutenant to the Force’s Chief Engineer (later re-titled Engineer-in-Chief) on 1 June 1915. He was to remain in post until hostilities ended. Traditionally, the British Army on campaign had obtained water from surface sources or shallow wells. However, the British Expeditionary Force soon needed to exploit groundwater from deep aquifers in French Cretaceous chalk and Belgian Paleogene sands, and eventually raised five Water Boring Sections Royal Engineers to do this, one for each army (Rose 2012a). King was innovative in generating a variety of water prospect maps, principally at scales of 1:100 000 and 1:250 000, for Belgium and adjacent parts of northern France, and in guiding the emplacement of >470 boreholes (Rose 2009b, 2012a).

Tannatt William Edgeworth David (1858–1934) had graduated from the University of Oxford in 1880, studied briefly at the Royal School of Mines in London, and emigrated to Australia in 1882 to take up appointment as an Assistant Geological Surveyor to the Government (Geological Survey) of New South Wales (Branagan 2005; Rose 2015b). His geological mapping over the next nine years contributed to the developing mining industry within the state. In 1891 he was appointed Professor of Geology in the University of Sydney, initiating a distinguished academic career. Deemed to be too old to volunteer for a commission on the outbreak of war, David was later to help found and raise an Australian Mining Corps (Battalion), in which he was granted a commission with the rank of Major, at the age of 57, with seniority from 25 October 1915. He arrived in France in May 1916 and served initially as Geological Adviser to the Controllers of Mines of the British First, Second and Third Armies. Later that year he was posted to the Inspector of Mines Office at the British Expeditionary Force General Headquarters. David was to guide work of the Tunnelling Companies Royal Engineers as these expanded from nine to a total of 25 between 1916 and 1918, together with three Australian companies, a further three from Canada, and one from New Zealand. By the middle of 1916 the British Expeditionary Force had c. 25 000 men actively engaged in tunnelling. Initially, their role was to tunnel mines beneath the fortified front line of the enemy and charge these with explosives that would be detonated to create a breach in the fortifications immediately prior to infantry assault. Later, as the front line came to be held more by artillery fire power than infantry manpower, mining was replaced by the construction of dug-outs to protect troops from artillery or aerial bombardment. David prepared geological cross-sections and innovative thematic maps, notably a series at scale of 1:10 000 (e.g. Fig. 5), that guided the work underground (Rose & Rosenbaum 2011).

Although King as a hydrogeologist and David as an engineering geologist initially worked in separate Engineer branches at General Headquarters, they co-operated on their own initiative and were eventually allowed to work together. Additional to their priority tasks, they contributed some advice used in preparation of ‘Tank maps’ to guide cross-county movement of the newly invented armoured vehicles (Anon 1922). They also provided advice on the winning of raw materials (Rose 2018b).

American military geologists

The US Army Corps of Engineers had developed from officers whose primary military duties centred on the construction and maintenance of fortifications, such as those described by Henderson (2018). These officers were combined with those of a, sometimes, separate branch that focused on topographical surveying into an organization with considerable experience in construction works. ‘The British and French governments made the arrival of American engineers in France their top priority after the United States declared war [on Germany] on April 6, 1917’ (US Army Corps of Engineers 2008, pp. 123–124). A brochure was quickly prepared (by 24 April 1917) on behalf of the Geology Committee of the National Research Council of the USA with ‘the purpose of stating succinctly and clearly the competency of the geologist in war service’ and duly ‘commended to the attention of commanding officers’

Fig. 5. Geological map of Wytschaete, Belgium, one of a set of 12 British maps at scale of 1:10 000, showing classification of ground according to its suitability for the construction of dug-outs. Shades of red indicate relatively ‘good’ (dry) strata, shades of blue-green ‘bad’ (wet) units, purple indicates alluvium in river valleys and black spots the sites of exploratory boreholes. From Anon (1922); see also Rose & Rosenbaum (2011) and Willig et al. (2015).
Later that year, in June 1917, Lieutenant General (later General of the Armies) John J. Pershing and his headquarters staff of an American Expeditionary Force (AEF) arrived in France. As part of the staff’s preparations for deploying the US 1st Infantry Division and subsequent combat and support units, Brigadier General Sherwood A. Chester and Colonel Ernest Graves of the US Army Corps of Engineers evaluated Allied military mining and water-supply operations on the Western Front and then asked for geologists to be attached to the AEF (Brooks 1920; Nelson & Rose 2012). Accordingly, Alfred H. Brooks took leave from the US Geological Survey to lead the requested effort in military geology and was commissioned as a Major (later Lieutenant Colonel) in the Engineer Officers Reserve Corps, followed by Captain (later Major) Edwin C. Eckel. In September 1917, they established a Section of Geology in General Pershing’s headquarters. As the AEF expanded, in July 1918 it approved Brooks’s plan to have six geologist officers with him at Pershing’s headquarters, place five more with each of two US armies, and assign two others for work along the lines of communication. However, hostilities ended on 11 November 1918 before Brooks could fill most of these appointments. By that time, four geologists served with Brooks at AEF Headquarters, two with the US 1st Army, one with the 2nd Army, and one within a Water-Supply Section: nine in overall total.

These geologists supplied information and advice about the soils and rocks to be encountered by the AEF in mining operations and in building and maintaining trench systems and other fortifications, constructing roads and railways, and seeking supplies of potable water. Active within only the final 14 months of the war, they followed French and British precedents, especially for water supply, but pioneered their own style in preparing geotechnical maps and reports. Deployed to the SE of the British operational area, they faced similar challenges in trench warfare, but these were commonly associated with Jurassic sedimentary rocks (Fig. 6) rather than the Cretaceous and Paleogene bedrock of the British region described by Doyle (2018).

The geologists were demobilized like other troops when the war came to an end. Brooks himself remained in France as geologist to the American Commission to Negotiate Peace and did not return to the US Geological Survey until August 1919.

Fig. 6. American diagrammatic cross-section across part of the Moselle valley near Pont-à-Mousson in NE France, showing Jurassic bedrock and Quaternary superficial cover, with indications of suitability for trench construction. From Brooks (1920).
He promptly published a benchmark analysis of how the AEF had used geology on the Western Front (Brooks 1920) and recommended that geology be included in future military training. He suggested peacetime collection of geological information for potential theatres of war and proposed that a ‘staff of geologic engineer reserve officers’ be organized within the US Army (Brooks 1920, p. 124), but that proposal was not adopted. However, the term ‘military geology’ to distinguish a new discipline had now entered American scientific literature (Pogue 1917) and thus the English-speaking world. It was quickly incorporated into the title of a book (Gregory 1918).

**German military geologists**

German forces were to make much greater use of geologists during the war, and from an earlier date (Häusler 2000a). Their use was pioneered by Captain (later Major) Walter Kranz (1873–1953; Fig. 7), who effectively founded twentieth-century military geology within the German armed forces (Rose et al. 2000; Häusler 2003; Willig 2018). Kranz had retired from service within the Engineer corps of the German Army on 22 March 1913, as a Captain, and been appointed to the Fortification Service of the Strasbourg Fortress. A border city long fortified by the French against potential German attack, Strasbourg had been regarded at the time of the Franco-Prussian War in 1871 as one of the strongest fortresses in France. However, German troops besieged and captured it. In a province subsequently annexed by Germany, it was re-fortified against re-capture by the French. Kranz published articles specifically on Militärgeologie (military geology) that initiated recognition of the subject (Kranz 1913, 1914) and in 1917 he completed studies for a doctoral degree in military hydrogeology.

Mobilized from the army reserve on the outbreak of war in August 1914, Kranz was assigned to government military geological work at Strasbourg in November 1914. There he suggested to his superior headquarters on 16 December 1914 that he should be entrusted with the investigation of problems related to the drainage and water supply of field positions, and to mine warfare. Soon he was promoting his subject as Kriegsgeologie (war geology) rather than military geology, to make its immediate relevance more apparent. He published several articles on this topic (e.g. Kranz 1915). His persistent persuasiveness achieved the desired result. In a circular dated 2 April 1915 the General commanding the Engineer Corps in the German Army’s supreme headquarters invited all Engineer Generals to make use of Kranz for advice. Moreover, on 21 May 1915 the Chief of Staff of the Field Army ordered that ‘the generals of the Engineers at the [individual] army headquarters should be informed that they could consult geologists, and that these should be made available to them on request’ (translated from Kranz 1927, p. 9).

In 1916, a geological organization as such was formed within the German Army, under the auspices of its (essentially geographical) Mapping and Survey branch (Häusler 2000a). Training for military geologists was provided from December 1917. By late 1918 a military geologist was attached to each army high command and a military geology unit to each of 28 Survey units (Vermessungsabteilungen). By the end of the War the German Army had made use of c. 200 men for their geological expertise and they had generated over 5500 geotechnical reports. A leaflet issued to guide the use of military geologists had a print run of 4000 copies.

According to Willig (1999) and Häusler (2000a), military geologist tasks in general related to the construction of field positions (especially trenches, dug-outs and mine tunnels, to minimize the use of time, labour and materials, and the risk of excavation collapse or water inflow); water supply (especially

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**Fig. 7.** Walter Kranz, pioneer of twentieth-century German military geology. From Rose et al. (2000); reproduced courtesy of the Archive for the History of Geology in Freiburg (Geologen-Archiv) at the Universitätsbibliothek Freiburg-im-Breisgau, by kind permission of Andreas Hoppe, per Hermann Häusler.
the siting of new boreholes and dams); quarrying or mining of raw materials (both aggregates for construction projects and reserves of economic significance, e.g. ores and coal); hygienic and technical problems (notably advice on problems of drainage, earthing of cables and route alignment for roads and railways); and other military problems (e.g. site selection for standing camps, ammunition dumps, heavy gun positions and airfields).

Specialist maps were innovatively generated from conventional geological maps for many key areas, primarily at the scale of 1:80 000 but later 1:25 000 for local use and 1:250 000 for more general planning. Typically these were Minierkarten (mining maps: see Willig 2018, fig. 6) to guide underground excavation, Wasserversorgungskarten to guide groundwater abstraction (water supply maps: see Rose 2009b), and Bau- oder Rohstoffkarten to guide quarrying for construction materials (construction or raw materials maps: see Fig. 8). At least one of the 28 geological units, that attached to Survey Department 13 (Geologengruppe de Vermessungsabteilung 13, Württemberg) is known to have compiled more detailed maps (13 sheets at a scale of 1:10 000) as well as 11 sheets at 1:25 000 plus two more general maps (Häusler 2000a). The German Army had intended to transfer the geological organization from Survey to Engineer command during 1918, so as to relate geologists more closely to their primary military clients, but hostilities ended in November 1918 before the change in command could be effected.

Fig. 8. Construction materials map, one of a set of maps illustrating how the same piece of ground can be mapped at a scale of 1:25 000 to depict also rock types (Gesteinsartenkarte), stratigraphic units (Geologische Karte), potential water supply (Wasserversorgungskarte) or water table depth and tunnelling conditions (Grundwasser- und Minier-Karte). Key: rock type indicated by colour (legend translation: (1) limestone; (2) sandstone; (3) sand; (4) gravel; (5) clay or marl; (6) loam); potential extraction site by circle; relative potential yield by circle size. The numbers 1–6 correspond with those in an accompanying table, where rock properties and potential uses are summarized for each rock type. From von Bülow et al. (1938).
German military geological work was to stimulate an extensive literature post-war. Kranz himself was to generate 170 published articles in his lifetime, about a third of them relating to military geology and most of these based on his personal experience during the war (Häusler 2003). Wilser (1921) quickly generated a textbook based on his own experience as the senior geologist within the wartime organization and edited (Wilser 1923–29) a series of 14 volumes that described the geology of the battlefields contested by German troops, on all fronts. A textbook by Kranz (1927) focused on engineering rather than military geology but was derived from his wartime military work. Further textbooks were to follow, as World War II loomed: by Wasmund (1937), based on theory rather than experience, and Kranz (1938), Mordziol (1938) and von Bülow et al. (1938), all based on skills learnt during World War I. More recently, Willig et al. (2015) have compiled an innovative geological World War I battlefield guide specifically for the Ypres region of Belgium, sourced from records both of the German forces and their opponents.

Austro-Hungarian military geologists

A presidential address in February 1916 to the Hungarian Geological Society (Schaafarzig 1916), published in both Hungarian (for local readership) and German (for Austrian readership), contained a significant section on Kriegsgeologie. It is evident from this that the relevance of geology to military operations was well understood in Austria-Hungary as well as Germany by this time – when the British Army possessed but a single military geologist, and the US Army none at all. By February 1918, the Austro-Hungarian Army had developed a military geological organization similar to that of the German Army and by the end of the war had made use of around 60 men as military geologists (Häusler 2000a). Ultimately there were 17 military geology units supporting Austro-Hungarian Military Survey units, each geological unit typically consisting of three to five geologists. A guidebook on Kriegsgeologie was printed on 3 March 1918 and the first of five courses to train military geologists was held in Vienna later that month. Other courses followed in May, June and August and a fifth was planned for the final months of the war.

Austro-Hungarian geologists, like their German counterparts, generated reports and thematic maps relating primarily to field fortifications, mine warfare, water supply and the quarrying of construction materials. They served on both the Western and Eastern fronts, in the Balkans, and on the 600 km-long and largely mountainous ‘Southern Front’ that extended from the Swiss–Austrian border eastwards across the Tyrol, the Dolomites and the Julian Alps to the Adriatic Sea near the port of Trieste. Its crucial section lay near the River Isonzo, and 12 Battles of the Isonzo were fought between Austro-Hungarian and Italian forces between June 1915 and November 1917, with over 500 000 casualties. The roles of Austro-Hungarian geologists operating in this region have been described extensively by Häusler (2000a, 2013) and more briefly by Angetter & Hubmann (2015).

World War II (1939–45)

World War II dawned with a greater perception of military applications of geology in the Union of Soviet Socialist Republics (USSR) and in Germany than elsewhere. From 1934 forces of the USSR had the use of a 123-page military geological textbook: Primenenie geologii na voine (Application of geology in war) that consisted of translations of the benchmark publications of King (1919) and Brooks (1920) published together (Sabine 1992). Sychev (1979) in The Great Soviet Encyclopedia, based on Ovchinnikov et al. (1945) and Popov (1958), noted that work was done in the USSR to study and generalize the military geological experience gained in World War I with regard to the location of defensive works and the carrying out of various types of military engineer work. Also, that military geological services were formed in virtually all the warring countries, implying their existence in the USSR although not recording specific details. Ovchinnikov et al. (1945) described how geology could be applied to fortification, mine warfare, water supply, roads, airfields and camouflage. They also provided an introduction to geological surveying, mapping and aerial photographic interpretation, in a book of nearly 400 pages that provided evidence of considerable experience in military geology. Smith (1964, p. 319) cited an American account claiming that ‘German intelligence sources reported that over 15 000 persons were employed in military geology in the USSR during the war years’. However, little record of this work is currently in the public domain and Betz (1984, p. 357) has inferred from the large number ‘that many [of the supposed military geologists] were actually working on problems assigned to branches of economic geology’.

Other countries were less well prepared. It is known that a Royal Geological Unit (Regio Reparto Geologico) was formed within the Engineer branch (Genio Militare) of the Italian Army and that it compiled a water supply map for use in North Africa showing the positions of wells and the depth to water, but its roles have yet to be described (Aldino Bondesan, pers. comm. 2018). Little is known of Japanese military use of geology (Yajima 2006). The work of military geologists is known, as in
World War I, mostly from British, American and German sources. However, whereas in World War I it was the relatively static trench warfare of the Western Front that required greatest geotechnical input, World War II came to necessitate support for more mobile forms of conflict and in a wider range of countries.

British military geologists

Initially, the British again made use of very few military geologists. Effectively ‘field force’ geologists as in World War I, single geologists served as staff officers within the Engineer branch at general headquarters – but in more than one theatre of operation (Rose & Rosenbaum 1993b; Rose 2011). Major W.B.R King (Fig. 9) served from September 1939 as the water supply officer with the new British Expeditionary Force sent to northern France, the same man in the same place and role as in World War I, until the Force was defeated and evacuated at the end of May 1940. His university and military protégé Captain F.W. Shotton also served as a water supply officer, from 1941 to 1943 with Middle East Command, based in Egypt but with responsibilities ranging widely across the Middle East and North Africa (Rose & Clatworthy 2008a). Captain (later Major) J.V. Stephens, recruited from the Geological Survey of Great Britain, served from 1943 to 1945 in Sicily and Italy (Rose & Clatworthy 2007a); see Rose (2018c, fig. 8). Also from 1943 to 1945, Major (later Lieutenant-Colonel) King succeeded by Captain (later Major) Shotton served with 21st Army Group preparing for or participating in the June 1944 liberation of Normandy and the subsequent NW Europe campaign that ended with Allied victory in Europe (Rose et al. 2006, 2010).

Their work focused initially on water supply (Rose 2012b) but broadened as conflict developed to include many aspects of engineering geology (such as site selection for the rapid construction of temporary airfields) and terrain evaluation (for cross-beach or cross-country trafficability). Thematic geotechnical maps were compiled to communicate technical information to non-geologist staff officers involved with the planning of military operations. For the amphibious and airborne landings in Normandy, these included beach trafficability maps at the scale of 1:5000 (Fig. 10), groundwater prospect maps at 1:50 000 and 1:250 000, and soils maps (to guide site selection for airfields and to indicate potential cross-country trafficability) at 1:250 000 (Rose et al. 2006, 2010).

Work by the small number of geologists was facilitated by resources made available at the Geological Survey of Great Britain and by reprinting, by the Geographical Section General Staff, of geological maps selected from the many published locally before the war. From October 1940 it was complemented by geophysical surveys made by detachments of 42nd Geological Section of the South African Engineer Corps: a 38-man unit that helped geologists to guide military well drilling for potable water in East Africa, the Mediterranean region and the Middle East (Rose 2018d).

In 1943, as British forces moved increasingly from defence to counter-attack, geologists were used to found two units to compile terrain intelligence for military use, the only occasions (other than as the South African section) when the British Army was to use geologists as teams rather than as individual staff officers. The Strategic Branch of the Geological Survey of India, based in the Survey’s headquarters at Calcutta (present-day Kolkata: capital of the Indian state of West Bengal), grew from its foundation in June 1943 to comprise two officers at the rank of Major (or equivalent) and six Captains, plus a Staff Captain as administrator and appropriate clerical, drawing office and ancillary staff (Rose 2005c). At Oxford in England, a Geological Section within the Inter-Service Topographical Department (Fig. 11) grew from four men appointed as Royal

![Fig. 9. Major W.B.R. King, Royal Engineers, the senior British military geologist of World War II; from Rose & Rosenbaum (1993b), reproduced by kind permission of his daughter Professor C.A.M. King and granddaughter Jane Ritchie.](http://pubs.geoscienceworld.org/books/book/chapter-pdf/4622026/01_sp473-18-104.pdf)
Fig. 10. Part of Sheet 74 Asnelles-sur-Mer of France 1:5000 map series, 1st edition January 1944; one of a set of ‘secret’ maps, compiled and printed for Allied forces, depicting beaches in Normandy selected for invasion, on D-Day in June 1944. Whole map illustrated and described by Rose et al. (2006); reproduced from the Shotton Archive by kind permission of the Director, Lapworth Museum of Geology, University of Birmingham.

Fig. 11. Members of the Geological Section of the Inter-Service Topographical Department, photographed in March 1945. From left to right, standing: Captain M.R.F. Ashworth (soil chemist in civilian life), Lieutenant (later Captain) J.R. Foster-Smith (mining engineer/geologist), Lieutenant (later Captain) W.R. Williams (economic geologist), Lieutenant (later Captain) A. Ludford (geologist), Captain W.E. Fraser (petroleum geologist), an unidentified RAF draughtsman, another draughtsman (probably Sapper Hunt) and the Section head: Major J.L. Farrington (economic geologist). Sitting: Captain A.D.M. Bell (petroleum geologist), Miss Jane Labey (Section typist) and Mr L.C. Huff (one of two geologists of the US Geological Survey’s Military Geology Unit who served with the Section from January to March 1945). Photograph and identifications courtesy of the late Dr Albert Ludford; from Rose & Clatworthy (2008b).
Engineers’ Captains in November (later one Major plus three Captains) to a maximum effective strength of 12 geoscientists by the end of hostilities (Rose & Clatworthy 2007b, 2008b). These two units were to generate a large number of specialist maps (e.g. Fig. 12) and reports, building on earlier such work by organizations staffed primarily by geographers. Thus, in the first year of the war, the British Army made use of only one uniformed military geologist, Major ‘Bill’ King (Fig. 9). In the final year it made use of at least 24: 12 at the Inter-Service Topographical Department in England at Oxford, eight at the Strategic Branch of the Geological Survey of India at Calcutta, two in Italy (Majors ‘Steve’ Stephens and ‘Bill’ Macfadyen: Rose 2018c), and two in NW Europe (Majors ‘Fred’ Shotton and ‘Dai’ Ponsford: Rose et al. 2006). Bill King was to draw on their experience to compile a textbook for the Royal Engineers published soon after the war ended (Anon 1949).

American military geologists

The Japanese attack on Pearl Harbor on 7 December 1941 brought the USA into World War II. The Geological Society of America, meeting at Boston later that month, provided a forum for geologists determined to contribute to the war effort (Nelson & Rose 2012). Ultimately this determination led to foundation of the Military Geology Unit of the US Geological Survey in July 1942. Based in Washington DC, this comprised in-house and other earth scientists and engineers tasked to gather terrain and related strategic intelligence. Price & Woodward (1942) urged in detail that geologists should be used for the interpretation of terrain for military operations, conversion of ground for military use, maintenance of supplies and communications, and miscellaneous other applications. Erdmann (1943, p. 1190) later recommended that a military geologist should be ‘a professional geologist of the widest range of sound training and field experience in areal mapping, engineering geology, geomorphology and the geology of unconsolidated materials’ and subsequently advocated applications of geology to terrain intelligence (Erdmann 1944).

As authoritatively described by Hunt (1950) and Terman (1998a), the Military Geology Unit compiled reports containing data about regions outside the USA as tables, text and maps (e.g. Fig. 13) for use by Allied forces, especially American and British. About 50 ‘Strategic Engineering Studies’ were completed in 1942, and at least 50 more in 1943. The Unit’s products contributed significantly to the Allied campaigns in Sicily and Italy from 1943, and complemented British geotechnical work associated with Normandy and the NW Europe Campaign in 1944–45. In 1944–45, the Unit deployed teams from Washington to US Army theatre headquarters in Europe and, more substantially, to the SW Pacific and Pacific Ocean theatres, principally to provide intelligence for strategic and tactical planning and prepared in World War II by the Military Geological Unit of the US Geological Survey, of Kikaiga-shima, in the Ryukyu Islands NE of Okinawa, Japan, showing terraces and inferred inland trafficability. Cropped from US Geological Survey & US Army Corps of Engineers (1945); see also Nelson & Rose (2012).

Fig. 13. Terrain map (original at scale c. 1:55 000), prepared in World War II by the Military Geological Unit of the US Geological Survey, of Kikaiga-shima, in the Ryukyu Islands NE of Okinawa, Japan, showing terraces and inferred inland trafficability. Cropped from US Geological Survey & US Army Corps of Engineers (1945); see also Nelson & Rose (2012).

Fig. 12. Simplified geological map of Hong Kong, at scale of 1:80 000, compiled at Oxford in 1944 by the Geological Section of the Inter-Service Topographical Department to accompany a report completed in January 1945. The key groups rocks by use of three principal colours, with colour intensity varied so as to increase to five the main units depicted: (1) pale yellow (surface deposits: Recent); (2) deep yellow (younger sedimentary deposits: Tertiary); (3) pale red (younger igneous rocks: Tertiary); (4) green/blue (older sedimentary deposits: Palaeozoic and Mesozoic); and (5) deep red (older igneous and metamorphic rocks: mostly Mesozoic). The coloured ‘rock groups’ are subdivided by shading or overprint to differentiate 10 categories and the key tabulates data for each of these categories in seven columns: (1) rock types; (2) rock characteristics (three sub-columns: structure, properties fresh, properties weathered); (3) terrain; (4) soils; (5) underground water; (6) construction materials; and (7) notes on undifferentiated rock groups, reliability, and sources. From Rose (2013), cf. Mackay (2018); reproduced by permission of the Royal Geographical Society’s Library.
advice to and (in the Pacific) participation in combat operations.

Numbers serving in the Unit increased from 10 professional personnel and one technical/clerical staff member in July 1942 to 80 professionals and 20 support staff in January 1945, as the war neared its end. Overall the total involved at least 88 geologists, 11 soil scientists, 15 other professionals and 43 support staff. Also, in total, the Unit produced 140 major terrain folios, 42 other major reports and 131 minor studies, in aggregate containing about 5000 maps, 4000 photographs and figures, 2500 large tables of data, and 140 terrain diagrams. Key components comprised terrain analysis for military purposes and data concerning rivers, potential road and airfield construction or repair, construction materials and water supply.

Like the British Army (Anon 1949), the US Army post-war was soon to publish a manual to show from experience how geology could be applied to military operations (Department of the Army 1952).

**German military geologists**

From 1937, as World War II loomed, a new military geological organization was developed in Germany (Häusler & Willig 2000), and in 1938 Germany occupied and annexed Austria. During the war, as comprehensively described by Häusler (1995a, b, 2000b) and summarized by Häusler (2018), this enlarged Germany was to make use of about 400 geologists to support its armed forces, most in the German Army but many also in the air force (the Luftwaffe, which operated all sites related to aerial defence, e.g. anti-aircraft gun batteries, as well as airfields), the paramilitary construction agency Organisation Todt (which built the fortification systems known as the West Wall and the Atlantic Wall, involving a peak workforce of about 1.5 million men), the Waffen-SS (which had its own military geological organization, with distinctive insignia), and even some in the German Navy (which operated batteries of coastal artillery as well as harbour and other shore installations, and planned for and against amphibious operations). Smaller numbers of geologists served within Milgeo (the military geographic branch of the Army, which prepared handbooks and maps for countries of actual or potential operational interest) and within an inter-service Forschungsstaffel zur besonderen Verwendung [z.b.V.] (research team for special use), a multidisciplinary unit developed for terrain analysis (Häusler 2007).

The establishment for the German Army’s military geology organization expanded to comprise 40 centres or teams (Wehrgeologenstellen) by November 1943, each team typically comprising two officers or officials qualified to post-doctoral status (Fig. 14), supported by three non-commissioned officers as technicians or assistant geologists, and four other ranks for less-skilled tasks, such as driving or typing. Team deployments by the end of the war had in total ranged from North Africa to northern Norway, and from France eastward far into the Soviet Union. The library and archive of the organization (including copies of over 5400 typewritten reports) was held near Berlin until the closing months of the war, when these documents were stored at depth in a salt mine at Heringen in central Germany to preserve them from Allied bombing. The mine was captured by American forces and its contents transferred to the United States, first to the US Geological Survey, some later to the Federal Records Center and finally to the National Archives and Records Administration at College Park near Washington DC. The typewritten reports

**Fig. 14.** Ferdinand Trusheim in the uniform of a Technischer Kriegsverwaltungsrat, (Technical War Administration Officer) the status usually assigned to military geologists given commissioned rank to serve as such with the German Army in World War II: the national emblem is worn above the right breast pocket, as by other members of the contemporary German Army, rather than on the sleeve (as by auxiliary forces). During the Battle of France, from May to June 1940, Trusheim served as the ‘Corps geologist’ with the German 7th Corps, part of the 16th Army, and later assisted Otto Burre in geological preparation for 16th Army’s role in Operation Sea Lion, the invasion of England scheduled for September 1940. Photograph taken at Berlin-Wannsee in 1942. From Rose & Willig (2002), reproduced courtesy of Drs Ursula and Hans Trusheim, per Dierk Willig.
Fig. 15. Map of the Brighton area of southern England, classifying ground in terms of its suitability for various construction purposes and as a source of construction materials (Pionierkarte = engineering map); prepared at a scale of 1:100 000 by German military geologists to assist planning for Operation Sea Lion, the German invasion of England scheduled for September 1940. Quarry sites are plotted by spots, colour-coded to indicate rock type (key to bottom right), on a simplified geological map. Colours used on the map as a whole are defined in a five-column key (bottom left of map) which indicates the corresponding rock type, its workability, stability and permeability, plus any remarks (such as suitability for trenches and dug-outs). From Rose & Willig (2004); reproduced courtesy of the US National Archives and Records Administration, College Park, MD, USA.
were mostly returned to Germany in the 1960s and are now preserved either in the Bundesarchiv-Militärarchiv at Freiburg-im-Breisgau or within the Bundeswehr Geoinformation Center of the modern German Army (Willig & Häusler 2012).

The range of case histories thus accessible to scholars includes examples of geological work done in haste to aid operational planning (e.g. for an invasion of England, scheduled for September 1940; Rose & Willig 2002, 2004, see Fig. 15) as well as longer-term projects to aid occupation and fortification (e.g. on the Channel Islands off the French coast; Robins et al. 2012). Häusler (2018) uses these and other sources to describe how over 60 geologists in total from the German Army, the Luftwaffe and the Organisation Todt contributed to the German occupation and fortification of Norway: a massive effort that helped to pioneer aspects both of rock mechanics and soil mechanics.

The Cold War (1947–91)

During the following Cold War, it is again the armed forces of the UK, USA and Germany for which military geological information is most accessible. Even so, relatively little has yet been placed in the public domain.

British military geologists

All the British military geologists who had served as such in World War II were demobilized at the end of hostilities. However, from 1949 a few geologists were recruited to serve as Royal Engineer officers in the British reserve army (the Territorial Army, Army Emergency Reserve or successor organizations) as systematically described by Rose & Hughes (1993a, b) and Rose & Rosenbaum (2017). Never exceeding eight in total in any year, they were committed to unlimited call-out liability in war and to a minimum of 15 days’ annual service in peacetime. They served on attachment to British regular forces worldwide, providing technical guidance for a wide range of military projects, exercises and operations, particularly with regard to groundwater abstraction, site investigation for construction projects, quarrying, stability of slopes and tunnels, and cross-terrain ‘going’. Several of them were to contribute to a new engineering geological textbook, sponsored jointly by the UK Ministry of Defence and the Institution of Civil Engineers (Anon 1976).

American military geologists

Post-war, the Military Geology Unit of the US Geological Survey did not disband, but transformed into a Section (and subsequently, in 1949, a Branch) of the Survey (Terman 1998b). Former Unit members were replaced as they returned to pre-war duties by younger scientists, to maintain continuity of expertise. The Branch continued to compile terrain intelligence on a global scale for much of the Cold War and during major periods of armed conflict. It was eventually discontinued in 1972, after making use of c. 150 geoscientists in total, but most of its functions passed to other US Geological Survey units or to the US Department of Defense.

Bonham (1997) compiled a list of c. 1500 US military geology reports and maps prepared between 1942 and 1975. In addition to these, it was noted that the Survey’s military geologists generated more than 200 reports of more general geological interest that were published as Survey bulletins and professional papers or in non-Survey journals. The reports listed generally include basic subjects such as rock types, soils, water resources, landforms and vegetation, as well as terrain interpretation for cross-country movement and for the construction of roads and airfields throughout the world. Reports on specific areas range from generalized texts with small-scale maps derived from published sources to detailed texts with large-scale maps commonly based on aerial photographic interpretation and, especially for Alaska and western Pacific islands, involving field mapping. Other reports deal with topics of interest in military geology without reference to specific areas. Most of the reports were prepared by teams, primarily of geologists but commonly also including soils scientists, botanists, climatologists and geographers, and were published anonymously.

Terman’s (1998b) analysis distinguished the evolution of seven principal administrative units and research programmes that evolved within the Military Geology Section and its successor organizations after 1945:

1. The Strategic Studies Section, operational 1945–72 and funded by the US Army Corps of Engineers and later by the US Defense Intelligence Agency, was the major production unit. Notably, it contributed to a comprehensive small-scale National Intelligence Surveys Program and to a Pacific Engineer Intelligence Program. The latter involved the compilation in Washington DC of seven series of thematic maps for most of SE Asia at a scale of 1:250 000.

2. The Pacific Field Program for the US Army Corps of Engineers 1945–62 was a research and mapping programme in areas formerly occupied by Japanese troops.

3. The Alaska Terrain and Permafrost Section of the US Army Corps of Engineers and the US Geological Survey carried out field studies 1947–65 on the surface geology and
permafrost features in Alaska and other Arctic areas. It compiled reports with maps and engineering interpretations, mostly of Alaska and at a scale of 1:250 000.

(4) The European Field Program, principally undertaken by a US Geological Survey team in association with the US Army Europe 1953–64, generated 24 military engineering geology maps at 1:250 000 for western Germany and 131 cross-country movement maps at 1:100 000 for the whole of Germany.

(5) The Austere Landing Site Program 1956–70 for the US Air Force compiled large-scale studies on arid lands, both inside and outside the USA, and on Arctic ice-free land.

(6) The Special Intelligence Element, established in 1959 by the US Army Corps of Engineers and the Defense Intelligence Agency, provided geoscience consultants to the special intelligence community.

(7) The Nuclear-Test Detection Program 1962–72 compiled studies assisting in the interpretation of global seismic signals, notably a five-volume Atlas of Asia and Eastern Europe at scale of 1:5 000 000.

The US Army Corps of Engineers also used geological expertise throughout the Cold War. Its geologists, civilians like those of the US Geological Survey, also often worked in teams comprised of geologists, hydrologists, soil scientists, engineers and other professionals, and often in collaboration with US Geological Survey geologists or those from other Department of Defense agencies. However, during the late 1960s and early 1970s some officers served in uniform with the job title ‘geologist’. Most military geology was, and still is, accomplished at the various Corps research laboratories, now combined as the Engineer Research and Development Center and with headquarters in Vicksburg, Mississippi.

Characterization of terrain has been an ongoing task for Corps research since at least the 1960s, when a series of terrain analogues was developed for regions outside the USA where it was thought the army could become involved, e.g. deserts or tropical areas (e.g. Kolb & Dornbusch 1966). This led to detailed ‘country studies’, characterizations of terrain, including geology, hydrology and geomorphology, compiled primarily by multi-disciplinary teams from existing data. Terrain information was provided as guidance for troops in the field as well as for training on US military bases. Analysis and interpretation of aerial photography were important parts of these efforts, but after the ERTS-1 satellite (Landsat-1) was launched in 1972, emphasis rapidly moved to the use of satellite imagery and all that it offered.

Other tasks undertaken by Corps geologists included tunnel detection, notably in Vietnam and Korea (Anon 1979; Eastler 2004), identification of potential drilling sites for water, and the location of engineering materials. Environmental assessment of army facilities within the USA also began during the later stages of the Cold War.

Articles in Underwood & Guth (1998), Ehlen & Harmon (2001), Harmon et al. (2014) and McDonald & Bullard (2016) provide many specific examples of the wide range of military geoscience applications that developed in the USA within the Cold War period and subsequently.

German military geologists

During the Cold War, following creation of an army (the Bundeswehr) within the Federal Republic of Germany in 1956, a new ‘geophysical’ service evolved, combining meteorological and geological expertise so as to provide advice on ‘going’, i.e. cross-country mobility, as discussed by Malm (2018), as well as a range of other geoscience-related tasks (Rose et al. 2000; Willig 2012). At its peak the service included about 20 full-time geologists, all civilians but with reserve army ranks for use on military exercises or operational deployment – including a geologist team specifically assigned to each corps of the German Army. Geological tasks varied with the region and, therefore, the geology concerned, but typically involved environmental protection, assessment of natural obstacles to cross-country movement, construction projects and water supply and drainage. In some areas, tasks involved with environmental protection became so numerous that the function of the geologists was more to help protect the environment than it was to help protect the nation state.

The Geophysical Service merged with the Army’s Geographical Service in 2003 to form the current Bundeswehr Geoinformation Center. Until 1993, German military geologists were active only within the borders of Germany, but thereafter they were deployed overseas, to support United Nations or Allied forces, e.g. in Somalia, Kosovo and (most recently) Afghanistan, typically to help develop secure water supplies by the appropriate siting of boreholes (Willig 2012).

Principal applications of military geology

‘Military geology may be defined simply enough as the application of geology to the art of war’ (Erdmann 1943, p. 1169). From the range of applications, noted above, that have emerged over c. 200 years, four stand out as of particular significance: those relating to (1) water supply, (2) construction of fortifications, (3) ground excavation by trenching, tunnelling and quarrying, and (4) terrain evaluation for military operations.
Applications relating to water supply in general lie outside the scope of this book. They have already been extensively documented in a companion volume (Rose & Mather 2012). However, the sections above show how potable water has long been recognized as a vital military resource and problems of water supply were amongst the earliest and most frequent tasks assigned to military geologists serving on both sides in World War I. They were still important in World War II and subsequent conflicts. Additional to the challenge of providing water to large numbers of troops concentrated on campaign, without a secure water supply no defended locality, however well-fortified and garrisoned, can withstand siege for long. Examples of problems encountered in providing water supply to fortified localities are the only aspect of military hydrogeology discussed in this volume. Mather (2018) provides some examples of how water supply was achieved in southern England during the fortification works of the eighteenth and nineteenth centuries, revealing innovative means of exploiting groundwater from sites underlain by Cretaceous chalk or Paleogene clastic sediments potentially subject to seawater intrusion. Papers on coastal fortification, ground excavation and terrain evaluation constitute the rest of the book.

Coastal fortification

Fortification is an ancient skill. Some fortifications in the Middle East range back to about 5000 years in age (Toy 2006). However, the earliest known military defences to be erected in Great Britain are late-Bronze Age and Iron Age hillforts: earthworks, originally reinforced or topped by timber palisades, which were constructed in large numbers during the thousand years before the beginning of the Christian era (Johnson 1978; Williams 1999). The Romans invaded Britain in AD 43, progressively captured the hillforts, and in the next c. three centuries initiated a programme of substantial stone-built fortifications both inland and at key coastal sites. Bromhead (2018) describes how a coastal fort from this period, constructed on an abandoned marine cliff eroded into a near-horizontal sequence of Early Cretaceous sandstones overlying mudrocks, has suffered damage in the 1700 years since its completion. This damage is inferred to be the consequence of a few major landslips rather than continuous creep downslope, and so to provide unusually long-term evidence concerning the nature and frequency of natural slope failure.

In the eleventh century, Norman conquest of England initiated a new phase of inland fortification that included castle building and extended through the medieval period. However, the next national programme of coastal fortification in England was initiated only in the sixteenth century, by King Henry VIII (Fig. 16). His scheme was enhanced in subsequent centuries, culminating in the mid-nineteenth century with fortification of the major naval bases in southern England at Portsmouth (Mather 2018), Plymouth, Portland, Dover, Chatham and the mouth of the River Medway, and Pembroke in south Wales: the largest scheme of fortification ever seen in Britain (Porter 1977; Crick 2012).

Fig. 16. Lindisfarne Castle, constructed in the sixteenth century on the coast of NE England on a site fortified by order of King Henry VIII. It occupies an eroded remnant of the Great Whin Sill, a dolerite intrusion of late Carboniferous age, in places >70 m thick, whose outcrop scarp has been partly fortified by Hadrian’s Wall of AD 122 and by several medieval castles (cf. Rose 2005d). Photo courtesy of Claire Rose.
Henderson (2018) provides an account of coeval fortification in the USA, to provide a defence against potential invasion by the British. Following national independence from colonial rule in 1784, the government of the USA soon approved construction of a ‘first system’ of forts at key locations along the country’s eastern seaboard, followed by a ‘second system’ early in the nineteenth century and, from 1816, an ambitious ‘third system’. Only 42 ‘third system’ forts were actually built, primarily on weak Quaternary sediments: some on Pleistocene drumlins or moraine, many on Holocene barrier islands, their geological setting being therefore very different to the sites of nineteenth-century forts in England described by Mather (2018).

The final article in this section of the book (Häusler 2018) moves the theme of coastal fortification into the twentieth century. It looks at Norway, whose rugged coastline of over 25 000 km has been eroded principally into a strong Precambrian–Paleozoic terrain, albeit with a locally thick Quaternary clay cover. During World War II, at least 63 German and Austrian geoscientists were incorporated into the German armed forces occupying Norway: an exceptional concentration of expertise. Most assisted construction of the northern part of the ‘Atlantic Wall’: in total a massive system of intermittent coastal fortifications that extended c. 2600 km in a near direct line from northern Norway south to the border of France with Spain, to defend the western boundary of German-occupied Europe against an expected Allied invasion. The professional experience they gained was to give significant impetus postwar to international developments in both rock mechanics and soil mechanics.

Excavation

For World War I, Doyle (2018) describes herein how geology influenced trench construction by British troops and the Germans facing them in the northern part of the Western Front: terrain across Belgium and part of northern France underlain by Cenozoic sands and clays or by Cretaceous chalk with a variable Quaternary cover. This was but one part of a complex of trenches (e.g. Fig. 17) that extended from the North Sea southwestwards to the border of France with Switzerland, and so crossing older and stronger rocks outside the operational area of the British Expeditionary Force. Willig (2018) goes deeper, to provide an overview of tunnelling by German and Austro-Hungarian military engineers.

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Fig. 17. Map of Allied defence excavations (trenches, dug-outs and mine systems: in red) and the opposing German works (in blue) for the Champagne-Argonne region of the Western Front in 1918. Numbers in key at base indicate: (1) locality, (2) fort of Séré de Rivières system, (3) Allied trenches and communications, (4) German trenches and communications, (5) mine system, (6) mine system of Berry-au-Bac. Reproduced by kind permission of Pierre Taborelli from Taborelli et al. (2017).
not on the Western Front (for which tunnelling by both sides has already been extensively documented, e.g. by Jones 2010), but on the relatively less well-known Eastern Front, facing Russia and its satellite countries. Twelve teams of military geologists assisted this work, comprising over 60 men in total. Rose (2018b) returns the theme to the Western Front, describing the formation and role of Quarrying Companies raised by the Royal Engineers. A wartime innovation, they produced the large quantities of ‘stone’ required for the enhancement or repair of the road and rail infrastructure essential to the British Expeditionary Force: at its peak a force of c. 1.5 million troops.

For World War II, Rose (2018c) extends his account of Quarrying Companies by describing their re-creation in 1940 and their wide deployment to support more mobile operations of the British Army, in circum-Mediterranean countries as well as western Europe. This is followed by a complementary account (Rose 2018e) for Tunnelling Companies of the Royal Engineers, focused on tasks in northern France, the UK, Gibraltar and Malta and so including rocks stronger than those encountered by such companies when these were first raised for service, for the Western Front in World War I. Mackay (2018) continues the tunnelling theme. He describes a railway tunnel through granite in Hong Kong, deliberately sealed by British troops during World War II as part of a programme of ‘route denial’ intended to inhibit access by invading Japanese forces. The tunnel has been subject to recent remedial work: a case history in a region noted for the intensive studies in engineering geology that now guide its major construction works. Route denial and route maintenance have both proved to be historically significant aspects of wartime military geology.

Finally, Bulmer (2018) brings the military tunnelling theme up to date by an extensive account of the tunnels recently created by insurgents in weak Cenozoic sedimentary rocks in the Mosul region of northern Iraq, to hide combatants and their materiel from aerial observation and attack, and of attempts by Iraqi government forces and their allies to locate them.

**Terrain evaluation**

The final section of this book contains articles that might loosely be grouped under the heading of terrain evaluation (terms such as terrain analysis or terrain appreciation being sometimes understood to imply a more specific scope when used in a British military context; Americans use only the term terrain analysis).

Military interest in terrain goes back to the earliest times … [but] It was not until after World War II that serious and sustained attention was given to the problem of evaluating and predicting terrain conditions [for military purposes] (Parry 1984, p. 570).

In former centuries, use of military geographers as staff officers to guide commanders in their use of terrain during campaigns was pioneered in the armies of France and Prussia, from the eighteenth century onwards. Topographical maps that illustrated terrain features in detail became an increasingly important military resource from this time. In the UK, the Ordnance Survey was founded in 1791 to undertake a national survey of Great Britain in the face of a perceived growing threat of invasion from revolutionary France (a survey completed in the nineteenth century and revised subsequently), but its origins arguably lie in military surveys of Scotland begun in 1747 following the Jacobite rebellion of 1745–46 (Seymour 1980).

In the American Civil War (1861–65), several generals, both Union and Confederate (e.g. William S. Rosecrans and Thomas ‘Stonewall’ Jackson) had topographers on their staffs who provided maps of the terrain to aid troop movements as well as to subsequently document the battlefields (Pittman 2000). Harrelson et al. (2018) provide a case history in which Union military commanders made tactical errors in planning their Red River Campaign in the southern USA by overlooking unique geological aspects of the terrain, including the river’s flashy nature, high sediment load, anastomosing channels and rapids.

From World War I onwards, topographical maps came to be supplemented by thematic maps generated by military geographers and military geologists. Examples from World War I include water supply and ‘mining’ maps generated by both sides on the Western Front (Brooks 1920; Anon 1922; Häusler 2000a; Rose 2009b; Rose & Rosenbaum 2011). The German and Austro-Hungarian armies, supported by larger military geological staffs than the Allies, created thematic maps of great variety and number (Häusler 2000a). In World War II, German military geologists again compiled thematic maps of many kinds for many regions (Häusler 1995a, b), and as Allied forces moved increasingly from defence to counter-attack, both the US Army (Nelson & Rose 2012) and the British armed forces (Rose 2005c; Rose & Clatworthy 2007b, 2008b) created military geologist units specifically to compile thematic maps and reports. Moreover, Rose (2018f) describes how Allied terrain evaluation in World War II was significantly enhanced by the interpretation of aerial photographs, a technique pioneered for the Royal Air Force and the British Army (and so for Allied forces in general) by a unit that included some distinguished geoscientists amongst its most
influential officers. Malm (2018) brings the book to a close with a review, from a German perspective, of the techniques developed over the last 100 years in order to predict cross-country mobility for wheeled and tracked vehicles, now a major factor in military operational planning and so a key component of modern terrain evaluation. Such terrain studies formed part of the planning for British operations to liberate the Falkland Islands in 1982 (Fig. 18), although then (as often in World War II) the thematic map was compiled urgently and in haste rather than as the result of a long-term study.

Concluding remarks

These few examples serve to introduce potentially wide-ranging military aspects of geology. During the nineteenth century the British Army included successive Inspectors-General of Fortifications (or senior officers of similar title: Porter 1977) responsible for major construction works both in the UK and overseas whose staff occasionally had access to geological information and military geologists such as J.E. Portlock (Mather 2018). Smith (1964, p. 313) accepted that during the Russo-Japanese War of 1904–05 (cf. Willig 2018) the Russian Army ‘used a number of geologists primarily as advisers in constructing fortifications’. Forts and fortifications were being constructed across much of Europe between 1815 and 1945 (Williams 1999; Kaufmann & Kaufmann 2014a, b) and Germany, at least from World War I onwards, was to make major use of military geologists in their development (Willig 2018; Häusler 2018). However, as throughout history, developments in weapon systems continued to make old fortifications obsolete, and to serve as catalysts for the development of new types of defensive structures.

Ditches have been dug to define regional boundaries or impede military movement for several millennia, and stone has sometimes been quarried in impressively large quantities for fortress construction. For example, the 135 km-long Hadrian’s Wall built by some 30 000 soldiers and labourers in

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**Fig. 18.** Part of the Falklands Islands Royal Engineers Briefing Map series GSGS 5453 edition 3, compiled at scale of 1:250 000 under the direction of the Engineer-in-Chief (Army), primarily to indicate ‘going’ in 1982. Grid intervals: blue at 10 km, black at 15′. Green = firm ground usually passable, white = light peat passable with care, orange = bad going passable with local advice, magenta = bog or rock not passable to vehicles. The ‘derivation and reliability’ shown in the map margin indicates a contribution ‘by RE [i.e. Royal Engineers] geologists’. In fact, only one geologist was involved, from the British reserve army, working for two days with an agronomist who had recently returned from the islands. They drafted a first edition which was printed in full colour 36 hours later. A refined second edition was printed within a week (L.R.M. Cocks, pers. comm. 2018.) © Crown copyright, reproduced by kind permission of the Copyright and Release Branch, Defence Geographic Centre, Feltham, UK.
the ten years following AD 122 to mark the northern boundary of the Roman province of Britannia, required more than 24 million stones and was flanked by a ditch (the Vallum) 5.4–5.9 m wide at the top and 2.6–2.9 m deep, part of a zone of entrenchment 37 m across and larger than any prehistoric earthwork (Moffat 2009). The Romans frequently created small-scale earthworks during siege operations, but large-scale excavation actually during a time of conflict was a major feature of the two World Wars rather than earlier history. Sapping (i.e. trenching) and mining (i.e. tunnelling) are ancient military engineering skills long used in siege operations, particularly after the development of artillery able to breach fortress walls and consequent changes in fortress design intended to withstand bombardment. Of these, tunnelling to develop facilities underground has many implications for military forces of the present day. Even before recent conflicts in Iraq that involved tunnelling (Bulmer 2018), Eastler (2004, p. 35) predicted ‘underground terrain may very well be the pivotal battlefield of the not so distant future’. Indeed, The Times newspaper (Anon 2018, p. 30) recently alleged, albeit without substantive evidence, that:

> Of the 10 000 large-scale [underground] military facilities estimated to exist, North Korea has almost half … [and] the capability to move up to 30 000 troops per hour through a network of deep tunnels into South Korea.

US military training is currently being revised in the light of experience in Iraq and Afghanistan and such perceptions: ‘The Pentagon is spending $500 million preparing American soldiers to fight underground as military chiefs reassess the likely battlefields of the future’.

Quarrying is a more recent significant military engineering skill. It became important in World War I because of the scale of near-static troop confrontation on the Western Front. German military geologists were then innovative in developing thematic resource maps, showing sites or regions for the quarrying of construction materials (building stone, sand and aggregates) and material of economic significance (e.g. coal and metalliferous ores). These maps helped to guide the construction of fortification systems by the Engineer corps. A significant proportion of German military geologist tasks was related to the winning of raw materials in occupied land (Rose et al. 2000). The Allies, fighting to defend their own terrain, made use more of local civilian than military geologist expertise for such tasks.

Raw materials also formed a significant proportion of German military geologist tasks in World War II. Fortification systems, such as the West Wall (bordering Germany and France) and the Atlantic Wall (that marked the western limit of German-occupied Europe), consumed vast quantities of aggregate for concrete in 1938–40 and 1940–44 respectively. The Atlantic Wall alone included c. 15 000 bunker and casemate complexes with outer walls of reinforced concrete 2 m thick, eventually absorbing c. 17 600 000 tonnes of concrete (Rolf 1988). More recent operations have been less demanding on construction materials, but still placed demands on military geologists, e.g. following conflict in the Falkland Islands of the South Atlantic in 1982, when the British Army operated a quarry near Port Stanley (Fig. 18) (Rosenbaum 1985).

Much military geology is but hydrogeology and engineering geology undertaken for military clients, although in wartime speed of completion is typically more important than cost-effectiveness. Terrain evaluation, however, remains an aspect of geology that has particular military as well as civilian significance.

Since the early 1950s the procedures for terrain evaluation have developed far beyond the ‘no-go’ outline overlays of World Wars I and II and this portion of the military art has been finally transformed into a military science (quoted by Parry 1984, p. 579).

Acknowledgements Permission to re-use illustrations is indicated in figure captions where appropriate. The authors are grateful to Jim Griffiths for reviewing this paper.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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