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Deep weathering of granitic rocks: A case of tunnelling in NW Spain

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ABSTRACT

This paper highlights a case of extensive development of saprolith from granitic bedrock in NW Spain. The weathering front at the study area extends to more than 250 m in depth. The drilling of a railway tunnel (Madrid–Galicia high-speed line) through the bedrock and saprolith resulted in significant technical issues and economic losses. Cross-sections revealing the 3D complexity of saprolith development are mainly based on fieldwork, boreholes, laboratory tests, and the excavation works. Saprock is always observed overlying unweathered igneous bedrock. Two saprolite facies, one clay-rich and the other clay-poor overlie the saprock; the recognition is based on several criteria. These deposits gradually thicken from the boundaries between the granitoid and metasedimentary roof pendants. Factors controlling saprolith development are discussed, and the chemical and mineralogical changes and trends that occur are described. Variations in some geotechnical properties and the loss of quality of the rock masses from an engineering perspective are also quantified.

1. Introduction

The development of residual soils covering granitic rocks is a widely known process (e.g., Girty et al., 2013; Ng et al., 2001; Oliva et al., 2003; Ollier, 2010; Sequeira Braga et al., 2002). Diverse changes in physical properties and petrographic features of granite occur during weathering. Overall, three main stages are usually distinguished in this process: (a) fresh rock, (b) saprock (i.e., partially weathered granite) and (c) saprolite (Power and Smith, 1994; Taylor and Eggleton, 2001; Graham et al., 2010). Saprock and saprolite, also collectively known as saprolith, are usually characterized by preserving the original fabric and structure of the granitic lithotype.

Mineralogically, biotite plays an important role in the alteration of granite rocks. For example, it may produce a local volume increase as it is transformed into hydrobiotite, vermiculite or interstratified biotite–vermiculite (Isherwood and Street, 1976; Jeong and Kim, 2003; Nettleton et al., 1970; Parizek and Girty, 2014; Taboada and García, 1999a). In turn, hydrolysis and hydration reactions induce the transformation of feldspars into clays and colloids which may migrate from the rock (Carrasco and Girty, 2015; Taboada and García, 1999b; White et al., 2001). On the other hand, the alteration progresses slowly in K-feldspar and quartz grains, so they commonly form an unaltered framework in saprolite. Hence, two main trends are differentiated in the weathering of plutonic rocks: (a) the biotite-dominated trend (Girty et al., 2013) and (b) the plagioclase-dominated trend (Nesbitt and Young, 1984, 1989).

From the environmental viewpoint, landslides associated with shallow covers composed of saprolite and soil are a well-known hazard (Bacellar et al., 2005; Durgin, 1977; Lan et al., 2003). The geotechnical properties of the weathered materials can also result in excavation and support issues during underground construction (De Abreu et al., 2007; Grasso et al., 2003; Guatteri et al., 2013; Romero and Clayton, 2006; Sousa and Einstein, 2012). Moreover, saprolith occasionally forms aquifers (e.g., Dewandel et al., 2006) whose size is greatly increased when weathering extends in depth. The presence of both groundwater and loose saturated deposits occasionally causes severe engineering problems during the excavation in railway projects, as occurred in the Nakayama tunnel (Jōetsu Shinkansen line, Japan) that needed important drainage works (Egger et al., 1982) or in the Ayas tunnel in Turkey (Mahmutoglu et al., 2006).

This research relates to a case of weathered granitoids tunnelled in NW Spain that caused significant technical issues and economic losses during the excavation works, especially due to the presence of saprolith. Ground investigations linked to the project (Madrid–Galicia high-speed railway) enabled the study of the weathering environment whose geological setting is presented. To do this, the main features of the geological units have been analysed from structural, chemical, mineralogical, geotechnical, and hydrogeological viewpoints.

2. Background

Two main subsections of high-speed railway are differentiated in NW Spain (Fig. 1): (a) "Puebla de Sanabria–Ourense" (currently under construction) with a length of 240.8 km, including 136.2 km projected through 38 tunnels; (b) "Ourense–Santiago de Compostela" (completed in 2011) reaching 87.5 km in length, with 31 tunnels (29.3 km of

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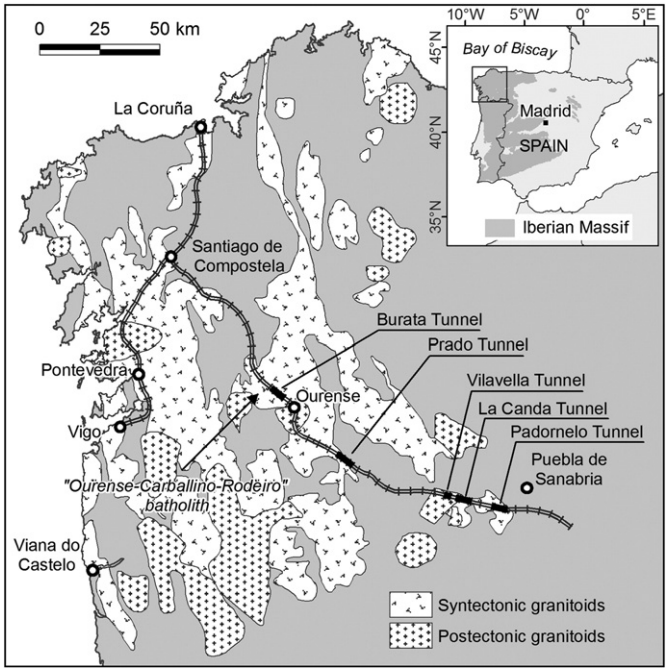

Fig. 1. Location of the main granitoids mapped in NW Spain. Tunnels where deep saprolite has been excavated at the Madrid–Galicia high-speed railway line are also indicated.

excavation). Altogether, 49 tunnels traversed mostly granitic rocks and a diverse suite of weathered rocks. The saprolith and soil rarely exceed 10–20 m in thickness, but in the Burata tunnel the weathering process was more intensely developed than in other areas. This tunnel, constructed between June 2006 and May 2010, is 3998 m in length and has a cross-sectional area of 85 m^2. It reaches a maximum depth of 150 m below the surface and 93 m on average. An emergency gallery (with a cross-sectional area of 13 m^2) transversally connected to the tunnel was built every 250 m along the length of the tunnel.

Both tunnel portals in Burata crossed saprolith and soil that were thicker than expected; despite this precedent, the weathering profile was not reviewed. At several sections throughout the projected tunnel, the preliminary geological surveys interpreted saprolite as material linked to fault zones with restricted development. Nevertheless, when drilling began using the New Austrian Tunnelling Method (NATM), the weathered rocks exhibited a very poor geotechnical quality. The saprolite behaved similarly to highly deformable soil, so the constructive solutions (i.e., steel ribs, shotcrete and bolts) were not as effective as expected. The measurements of convergences during construction revealed a reduction of the theoretical tunnel profile of over 10% (in area) on critical sections excavated in saprolite. It was necessary to build in some sections a concrete inverted arch at the tunnel bottom, and the support was reinforced (Fig. 2) with umbrellas of subhorizontal micropiles, injections and jet-grouting (Castells et al., 2006). Additionally, the Engineering Geology Research Group based in the University of Oviedo conducted an urgent geological survey. New boreholes and fieldwork should help to identify unknown roof pendants and weathered rock masses before they were crossed by the tunnel.

Saprolite saturation also significantly complicated the tunnelling due to the ground permeability and the hydrostatic pressure reached at depth (occasionally greater than 1 MPa). During the excavation, water drained into the tunnel (>20 l/s) mainly along granitoid–roof pendant boundaries. It was necessary to drill horizontal drainage wells to drawdown the groundwater table. The piezometric fall triggered a subsidence process that was monitored; a surface settlement of up to 10 cm was measured, although it did not cause structural damage (López-Fernández et al., 2013). The tunnel construction was delayed for two years and the cost increased by 46 million Euros.

As a result of the constructive experience gained during the tunnelling of Burata, the geological explorations were performed more rigorously in other areas of the railway. This enabled in an additional four tunnels (La Canda, Vilavella, Padornelo, and Prado) the identification of saprolite at depth, making it possible to optimize the technical solutions from the start of drilling.

3. Geological setting

The bedrock in northwestern Spain corresponds to internal zones of the Iberian Massif, a cratonic block related to the Hercynian orogeny. Specifically, in this study area, the batholiths are the dominant rock masses (Fig. 1) and intruded (over the course of several events) into a basement that consists of Precambrian and Cambro-Ordovician units (Capdevila et al., 1973; Dallmeyer et al., 1997; Pérez Estaún et al., 1991). The metasedimentary roof pendants are largely composed of mica schist, quartz schist, quartzite and paragneiss, with interbedded volcanic or subvolcanic layers. In these rocks, up to three deformation phases have been differentiated (Marcos, 1973).

Three associations of granitoids are distinguished depending on the compositional characteristics and their syntectonic or post-tectonic emplacements (Bellido et al., 1992; Corretgé, 1983): (a) syntectonic calc-alkaline granitoids; (b) syntectonic to late-tectonic peraluminous granites; and (c) post-tectonic calc-alkaline granites. Syntectonic tonalite–granodiorite–monzogranite (TGM) plutons are the oldest granitoids. They are composed of amphibole–biotite and quartz diorites, tonalites, biotite granodiorites (the most common lithology) and biotite–muscovite monzogranite. This lithological association is characterized by high K-content and represents I-type magmatic series (Galán et al., 1996). Syntectonic peraluminous granites are the most prevalent granitoids in NW Iberia. They include peraluminous muscovite–biotite to muscovite monzogranites, with minor feldspathic granites and aplites; all autochthonous, subautochthonous and allochthonous anatectic granites are included. This group corresponds to peraluminous rocks characterized by low-Ca and Ti content, and represents S-type magmatic series (Cuesta and Gallastegui, 2004). Concerning the post-tectonic association, calc-alkaline and subalkaline granitoids form the largest plutons. They have features closely related to the syntectonic T–G–M.

In this case, the Burata tunnel extends through the "Ourense–Carballino–Rodeiro" batholith. This intrusive body represents a typical example of the late Variscan post-kinematic magmatism in NW Iberia, which was intruded across the boundary of two different belts of deformation (Barrera et al., 1989). It is mainly composed of peraluminous (two mica; usually muscovite > biotite) calc-alkaline granitoids

Fig. 2. Excavation procedure in the Burata tunnel based on the top-heading and bench method (with a micropile umbrella in this photo).