Bio-mediated ground improvement: from concept to field application

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Biomineralization can be used as ground improvement method, for a wide range of geo-engineering applications, like mitigation of liquefaction and associated damage, improving the stability of dikes, dams, levees and slopes, reducing the permeability of underground leaking structures or stopping or diverting subsurface transport of contaminants by forming impermeable or reactive barriers. Most studies on applied biomineralization involve the precipitation of calcium carbonate, in particular by urea hydrolysis. In this process urea hydrolyzing bacteria are introduced in the subsurface and supplied with urea and calcium chloride. By hydrolyzing urea, the bacteria produce ammonium and carbonate. The carbonate precipitates with calcium carbonate and remaining ammonium chloride is removed. The calcium carbonate crystals form a binding cement between the soil particles while (partly) filling up the pore space, which increases the strength and stiffness of the soil and reduces the permeability. Using an empirical approach the feasibility of MICP by urea hydrolysis as ground improvement method has been demonstrated at full scale using conditions and techniques as used in practice, both as single point injection or over a horizontal distance using screens of injection and extraction wells. Engineering parameters correlated well with $CaCO_3$ content or dry density [1]. At the same time, a more fundamental approach was used to improve our understanding of the MICP process that involved multiple components including bacteria and multiple chemical species that are subject to both kinetically controlled and equilibrium reactions over multiple phases, undergoing transport in porous medium with changing porosity and permeability. Understanding of these processes was required to enable control of the *in situ* distribution of bacterial activity and reagents and the resulting distribution of $CaCO_3$ and related engineering properties. The combined approach of theory, experiments, modeling and monitoring has resulted in the first field applications in which biomineralization was used to cement gravel layers in order to improve borehole stability during horizontal directional drilling [2].

[1] Van Paassen, LA, Ghose, R, Van der Linden, TJM, Van der Star, WRL and Van Loosdrecht, MCM, 2010. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, **136(12)**: 1721–1728 [2] Van der Star, WRL, van Wijngaarden-van Rossum, WK, van Paassen, LA, van Baalen, LR, van Zwieten, G, 2011, *Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering*, *12 -17 Sep 2011, Athens, Greece*, 85-90.

$^{40}Ar/^{39}Ar$ cooling dates and deformation history on the southern flank of the Thor-Odin dome BC: tectonic implications of overlapping compressional and extensional regimes in the Paleocene-Eocene.

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The southern flank of the Thor-Odin dome comprises an ~12 km thick S-dipping panel of amphibolite to granulite facies rocks, the lower half of which is migmatitic. Throughout the structural section the rocks have a pervasive composite transposition foliation, with rootless folds, folded by syn- and refolded by post-metamorphic NE verging folds. Metamorphism and the youngest stages of ductile deformation are Late Cretaceous to Eocene and young progressively down section. On the basis of cross cutting granitoids dated by U-Pb studies, transposition and folding had ceased by: (i) 73 Ma at the highest structural levels (e.g. in the southern part of the study area near Whatshan Lake and west of the dome at Joss Mountain); (ii) 64 – 62 Ma (in the central section west of Arrow Park lake); (iii) ~58 Ma on the upper margin of the dome at Cariboo Alp; and, (iv) ~56 – 54 Ma within the dome. Cooling from the thermal peak of metamorphism to ~300°C occurred between 62 and 52 Ma on the basis of $^{40}Ar/^{39}Ar$ cooling dates. Thor-Odin dome and its southern flank lie in the footwall of the ~55 Ma and younger, E-dipping Columbia River normal fault. Proposed models for the exhumation of the dome and overlying rocks on the southern flank include extension, extrusion or diapirism (with an erosional contribution).

$^{40}Ar/^{39}Ar$ cooling dates on hornblende, muscovite and biotite from 80 samples at all structural levels were studied in order to place constraints on the timing of the exhumation over a temperature range of ~600 to 300°C. Hornblende $^{40}Ar/^{39}Ar$ cooling dates (calculated closure temperatures from 500 - 600°C) are ~62-58 Ma at the top of the panel, ~57-56 Ma in the middle, and ~55-53 Ma near the upper margin of the dome. Hornblende $^{40}Ar/^{39}Ar$ data from migmatites in the dome are disturbed and do not produce meaningful dates. Biotite cooling dates (280 - 350°C) are ~52-51 Ma throughout the 12 km thick structural section, including the dome. Since rocks from all different structural levels cooled through ~300°C at the same time the structural section was tilted prior to cooling or cooling rates were extraordinarily high. 51-50.5 ± 0.2 Ma muscovite dates from greenschist-facies muscovite intergrowths in extensional structures in the dome, grew below their closure temperature and date late stage extension.

The downward younging progression of deformation and the thermal history are consistent with that of a highly strained crystalline sheet that was deforming progressively as it overrode a basement ramp, the Monashee ramp imaged in Lithoprobe seismic reflection profiles 6, 7 and 8. Exhumation and cooling as a result of syn-convergent extension in the upper part of the structural section was ongoing during the last stages of transposition and folding in the dome in the Late Paleocene to Early Eocene. By ~51 Ma, extensional structures were active at all structural levels reflecting crustal scale extension and exhumation via normal faulting linked to continuing motion on the Columbia River and possibly the Okanagan Valley extensional fault systems.