Maqarin (Jordan)

Description: The Maqarin Natural Analogue Project was initiated in 1989. Phase I (Alexander, 1992), continued in 1991 with Phase II (Linklater, 1998), Phase III in 1993 (Smellie, 1998) and Phase IV in 1999 to be completed in 2005 (In preparation). A synthesis of the project up to 1998 is presented in Alexander and Smellie (2000) and repository performance assessment implications are discussed in Smellie et al. (2002).

The Maqarin site, located in NE Jordan (Figure 1), appears to be unique in that the hyperalkaline groundwaters in the area are the product of leaching of an assemblage of natural cement minerals produced as a result of high temperature-low pressure metamorphism of marls (i.e. clay biomicrites) and limestones.

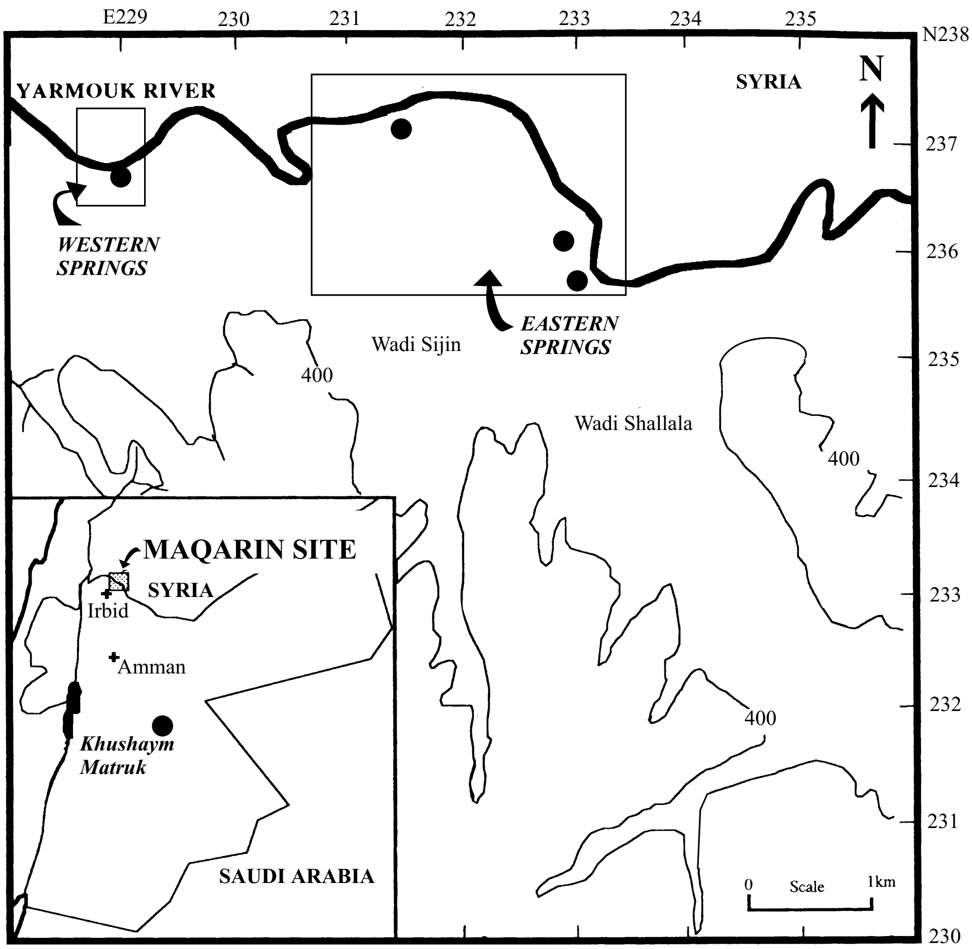

Figure 1: The Maqarin analogue sites: Western Springs, Eastern Springs and Khushaym Matruk; the Daba region in Central Jordan is located approximately midway to the west between Amman and Khushaym Matruk.

Whilst Phase I and Phase II were very much site-specific and process oriented (e.g. studies of the source term and its interaction with the host rock; testing the applicability of available thermodynamic data to hyperalkaline conditions; predicting the extent of high pH water/rock interaction using coupled models etc.), Phase III provided a more regional perspective to the geological and hydrogeochemical evolution of the entire cementitious system. Phase IV has focussed on resolving the remaining open questions from Phases I-III involving: a) definition of path lengths and description of flow pathways, b) dating the system (including the near-field cement and the secondary far-field interactions), c) rock matrix diffusion and clay stability in the altered far-field, d) source term definition and longevity of C-S-H phases; and e) coupled code modelling. These studies have centred largely on the Eastern Springs area, apart from the clay stability studies which have been carried out above the water table at the locality of Khushaym Matruk in Central Jordan.

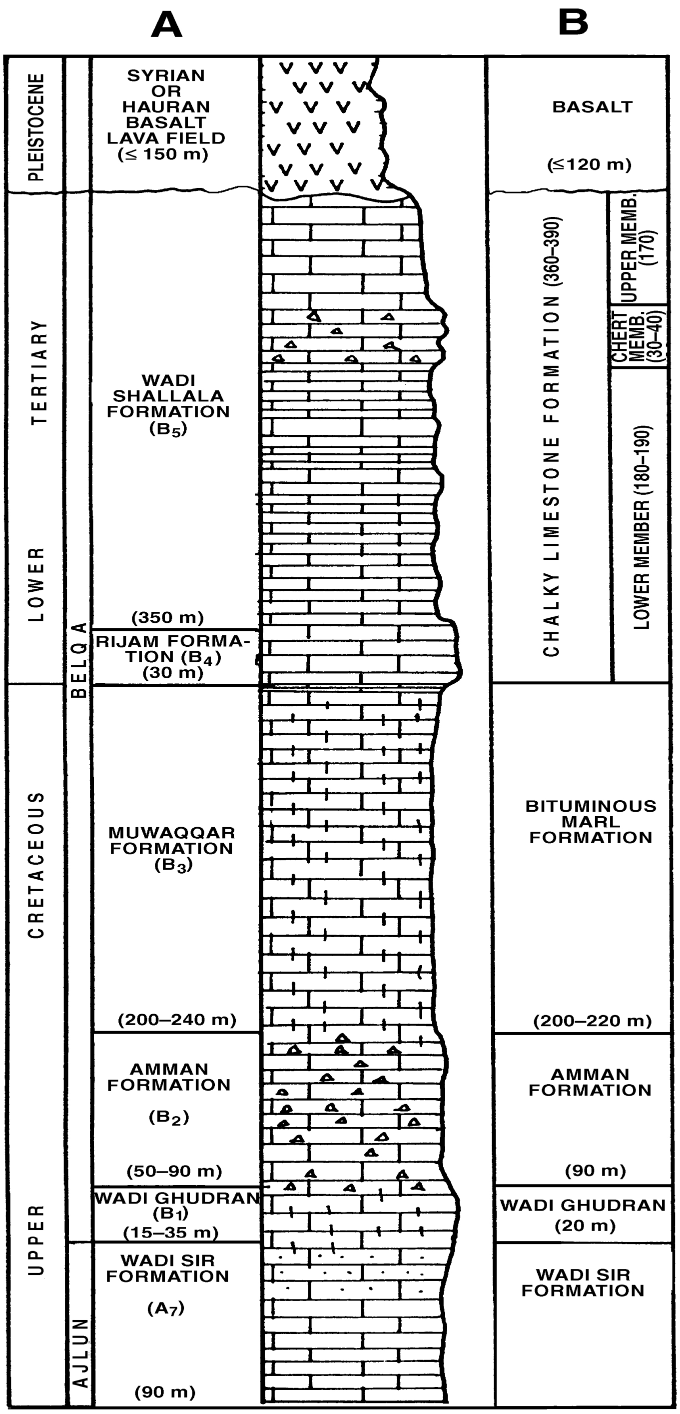

Figure 2: Generalised stratigraphical column showing the major geological units; the 'cement zones' are located close to the interface between the Bituminous Marl and the overlying Chalky Limestone Formation (A = regional stratigraphy; B = Maqarin stratigraphy).

Geologically, the Maqarin area comprises Cretaceous-Tertiary carbonate rocks overlain by Quaternary basalts, soils and alluvium (Figure 2). The E-W trending Yarmouk River Valley is a relatively recent geomorphological feature, having eroded through some 400 m of the Irbid Plateau, exposing the Bituminous Marl Formation which is overlain by the Chalky Limestone Formation, in turn capped by basaltic lava flows. There is no evidence that the Yarmouk Valley is structurally controlled by tectonic events associated with the Jordan Rift Valley system.

Regionally, the exposed strata show very little deformation and are almost horizontal to gently dipping (to the north). At the Eastern Springs locality, the Bituminous Marl Formation has been slightly uplifted by a N-S trending anticline which plunges to the NE. At a local scale the heterogeneity of the system is underlined, in part explained by karst features and gravity tectonics (i.e. slumping) facilitated by the hillslope angles (~ 45^{o}). Less is known from the Western Springs locality where talus and colluvium cover most of the hill slopes. There is, however, some indication of a N-S trending fault system associated with localised shearing and rotation. Some evidence also exists of gravity slumping features.

Whilst earthquake shock is not seen as a possible mechanism for creating fissures and joints directly in the rock, it may be a significant factor in triggering landslides, which in turn may have activated spontaneous combustion in the Bituminous Marl Formation to produce the metamorphosed “cement zones”, and subsequently the formation of the hyperalkaline groundwaters in the area. The actual period of combustion is uncertain; geomorphological considerations suggest a probable date to around 600 ka, and certainly not earlier than 150 Ka. More hypothetically, a second, later phase of landslides might also be considered to explain the geomorphological features (potentially also triggering combustion) observed at the Western Springs area. These two phases of landslip activity indicate that the Eastern Springs system is geologically older than the Western Springs system.

Reactivation on a smaller scale may be expected to be recurrent, rapidly triggered by heavy rainfall and more gradually, over longer timescales, by continued lateral erosion of the Yarmouk River. This may account for the periodic sealing and reactivation of hyperalkaline groundwater conducting fracture pathways, as indicated by mineralogical studies and field observations.

With respect to hydrogeology, at the Eastern Springs site the young, near-neutral groundwaters, which interact with the metamorphosed cement zones located at and close to the top of the Bituminous Marl Formation, originate mostly from direct recharge through the overlying Chalky Limestone Formation. In addition, some mixing takes place close to the limestone/marl interface with older regional groundwaters, which in the Maqarin region flow generally from the central plateau northwest to the Yarmouk River Valley. Following interaction with the cement zones, the resulting hyperalkaline groundwaters discharge as seepages within the Adit A-6, at rail and road cuttings and sporadically close to the Yarmouk River bed. In the Western Springs area, however, the waters originate totally from rapid vertical recharge into the Chalky Limestone Formation at the plateau south of the Western Springs location, facilitated by widespread open karst features. These groundwaters are subsequently channelled along the limestone/marl interface to interact with the metamorphosed cement zones. The resulting hyperalkaline groundwaters eventually discharge through a thick colluvium sequence along the Yarmouk Valley at an elevation of 1-4 m above the river bed.

Hydrogeochemical and isotope studies largely support the hydrogeological conceptualisation of the major groundwater flow pathways. The recharge groundwaters are meteoric and local in origin, of normal pH and dilute bicarbonate in type, contain measureable tritium, and are the probable precursors of the high pH groundwaters. Interaction of the normal pH groundwaters with the metamorphosed cement zones has produced two chemically distinct high pH groundwaters; Eastern Springs Ca-OH type and the Western Springs Ca-K-Na-OH-SO_4 type. Both types are believed to be older than 40 years at least (tritium-free), although minor amounts of tritium (~4 TU) in some samples may indicate slightly younger ages if mixing with recent recharge waters is excluded. The absence of thermonuclear ^{36}Cl would appear to be consistent with recharge prior to 1950.

A possible scenario is that the Eastern Springs area groundwater circulation has occurred over a much longer timespan and that readily soluble mineral phases are already completely dissolved. This supports the assumption that the Western Springs groundwaters represent the first pore volume discharging from the metamorphic zone, and that the Eastern Springs groundwaters represent later, more dilute, discharge. This is consistent with the field observations which suggest that the Eastern Springs system is geologically older than the Western Springs system, and is also consistent with the hydrogeochemical modelling. At both sites the resultant hyperalkaline leachates propagate as high pH plumes, extending some 200-400 m through the unmetamorphosed biomicrites to the River Yarmouk. Evolution of these plumes, in terms of hydrochemistry and mineralogy, has been studied in detail.

Based on the conceptualisation described above, the very detailed mineralogical evaluation of the metamorphosed cement zone, prior and subsequent to interaction, the mineralogical paragenesis associated with the formation and evolution of the propagating hyperalkaline plume, the potential influence of colloids, microbes and organics, and the geochemical and predictive modelling of this high pH system, have resulted in several conclusions of direct importance in assessing the long-term performance of a LILW cementitious repository.

Relevance: The three sites studied in Jordan appear to represent three different stages in the theoretical evolution of a cementitious repository for the disposal of low- to intermediate-level wastes (LILW). The three stages are: 1) early, high pH Na/KOH leachates (Western Springs, Maqarin), 2) intermediate, lower pH $Ca(OH)_2$ buffered leachates (Eastern Springs, Maqarin), and 3) late, lower pH silica dominated leachates (Daba region in central Jordan). Furthermore, the Kushaym Matruk study, in central Jordan, has direct input to the clay/leachate interactions expected to influence the long-term stability of clay backfill materials and clay-based host rocks.

Position(s) in the matrix tables: The Maqarin study illustrates cement/clay stability/degradation in the near-field matrix table and the evolution and propagation of a high pH plume in both the near-field and geosphere matrix tables.

Limitations: The Maqarin biomicrites differ considerably from a crystalline or clay-based repository host rock in that structurally they represent a very open and hydraulically transmissive system, in addition to being chemically dissimilar. Furthermore, the small amounts of clay (5-20 vol.%) complicate analysis and interpretation of clay stability under high pH conditions. Moreover, all groundwater/colloidal/microbe samples have been collected under oxidising conditions not expected at repository depths.

There is no information regarding the source term (i.e. metamorphosed cement zones) from the Western Springs site; this is a limiting factor in further understanding this site as representing the initial stage (high Na/KOH) in the early evolution of cement reaction and degradation.

Quantitative information: The most quantitative information has resulted from the mineralogical studies, which correspond closely to the observed and predicted behaviour of industrial cements (source term) and the evolutionary sequence of mineralogical reactions accompanying the propagation of a hyperalkaline plume. Modelling these reactions, despite the simplified modelling approaches used and the inadequacies of the thermodynamic data base, shows a good correlation with observations.

Uncertainties: Because of the general complexity of the systems studied, and therefore the difficulty in establishing the physico-chemical boundary conditions, the uncertainties will tend to be medium to high.

Time-scale: Relevant time-scales addressed by the study include archaeological (1000 – 10 000 years) and geological (Quaternary <2 Ma or >2Ma).

PA/safety case applications: The SKB-97 (1999) safety case used the Maqarin observations as support for long-term durability of the concrete barrier system. This included the hydrogeochemical processes and parameter values relating to: a) released hydroxides due to leaching; b) CSH and CASH phases, c) zeolite phases, d) pH reduction due to reaction with silicate minerals, and d) colloids/microbes/organics. In addition, ‘Blind Modelling’ (i.e. testing of geochemical codes and thermodynamic databases) and development of the hyperalkaline plume scenario, were also important issues addressed.

The NAGRA safety case for the Wellenberg L/ILW site, presently being prepared for publication, made wide use of the Maqarin studies.

Communication applications: Previous uses of the analogue in communication and dialogue material for different audiences include official SKB and NAGRA brochures, the SKB mobile exhibition and its inclusion in the CEC-coordinated natural analogue video ('Traces of the Future').

References:

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Added value comments: In the absence of the Phase IV documentation, which addressed various issues specifically to improve the value of the Maqarin as an analogue (see above), it is difficult to see how it can be better used apart from the testing and validation of improved coupled modelling approaches.

Potential follow-up work: Further field drilling and characterisation investigations are necessary to fully understand the Western Springs site. It could then be more quantitatively integrated into the overall conceptualisation of the area, in particular as representing the initial stage (high Na/KOH) in the early evolution of cement reaction and degradation. Much of the Eastern Springs area is now destroyed due to the construction of the Unity Dam on the Yarmouk River, due for completion in 2005.

Keywords: Natural cement, hyperalkaline fluids, high pH plume, model testing, clay stability.

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