Hydrogeology of a fractured shale (Opalinus Clay): Implications for deep geological disposal of radioactive wastes

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Abstract As part of the Swiss programme for high-level radioactive-waste disposal, a Jurassic shale (Opalinus Clay) is being investigated as a potential host rock. Observations in clay pits and the results of a German research programme focusing on hazardous waste disposal have demonstrated that, at depths of 10–30 m, the permeability of the Opalinus Clay decreases by several orders of magnitude. Hydraulic tests in deeper boreholes (test intervals below 300 m) yielded hydraulic conductivities $<10^{-12}$ m/s, even though joints and faults were included in some of the test intervals. These measurements are consistent with hydrogeological data from Opalinus Clay sections in ten tunnels in the Folded Jura of northern Switzerland. Despite extensive faulting, only a few indications of minor water inflow were encountered in more than 6,600 m of tunnel. All inflows were in tunnel sections where the overburden is less than 200 m. The hydraulic data are consistent with clay pore-water hydrochemical and isotopic data. The extensive hydrogeological data base – part of which derives from particularly unfavourable geological environments – provides arguments that advective transport through faults and joints is not a critical issue for the suitability of Opalinus Clay as a host rock for deep geological waste disposal.

Résumé Dans le cadre du programme suisse de stockage de déchets hautement radioactifs, une formation argileuse du Jurassique, l'argile à Opalinus, a été étudiée en tant que roche hôte potentielle. Des observations dans des cavités dans l'argile et les résultats du programme de recherche allemand consacré au stockage de déchets à risques ont démontré que, à des profondeur de 10 à 30 m, la perméabilité des argiles à Opalinus décroît de plusieurs ordres de grandeur. Des essais hydrauliques dans des forages plus profonds (intervalles de test à une profondeur de plus de 300 m) ont donné des conductivités hydrauliques inférieures à 10^{-12} m/s, même lorsque des fractures et des failles existaient dans certains des intervalles d'essais. Ces mesures sont conformes aux données hydrogéologiques tirées du recoupement des argiles à Opalinus par dix tunnels du Jura plissé du nord de la Suisse. Malgré une tectonique intense, peu de manifestations de faibles venues d'eau ont été rencontrées dans plus de 6600 m de tunnel. Toutes les venues d'eau se sont produites dans des sections de tunnel où le recouvrement est inférieur à 200 m. Les données hydrauliques sont en bon accord avec les données hydrochimiques et isotopiques de l'eau porale des argiles. En se basant sur le grand nombre de données hydrogéologiques, qui portent en partie sur des environnements géologiques particulièrement peu propices, on peut avancer que le transport advectif le long des failles et des fractures n'est pas un facteur susceptible de remettre en question le choix de l'argile à Opalinus comme roche hôte pour le stockage de déchets radioactifs en formation géologique profonde.

Resumen Dentro del programa suizo de eliminación de residuos radiactivos de alta actividad, se está investigando la posibilidad de utilizar unos esquistos Jurásicos (Arcilla Opalina) como depósito geológico. Las observaciones efectuadas en pozos en arcilla y los resultados de un programa de estudio alemán sobre eliminación de residuos peligrosos han demostrado que, a profundidades de entre 10 y 30 m, la permeabilidad de la Arcilla Opalina decrece en varios órdenes de magnitud. Los ensayos hidráulicos realizados en sondeos más profundos (en intervalos situados a más de 300 m) proporcionaron conductividades hidráulicas inferiores a 10^{-12} m/s, pese a que algunos de los intervalos interceptaban juntas y fallas. Estas medidas son coherentes con los datos hidrogeológicos de las secciones de Arcilla Opalina existentes en 10 túneles del Jurásico Plegado, al norte de Suiza. A pesar de las fallas extensivas, apenas se hallaron indicios de entrada de agua en los más de 6.600 m de túnel. Todos los flujos tenían lugar en secciones del túnel que soportan sobrecargas inferiores a 200 m. Los datos hidráulicos son coherentes con los datos hidroquímicos e isotópicos del agua intersticial de las arcillas. Los abundantes datos hidrogeológicos –parte de los cuales proceden de medios particularmente desfavorables desde el punto de vista geológico– proporcionan argumentos de que el transporte advectivo a través de fallas

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y juntas no es un aspecto crítico en lo que respecta a la idoneidad de la Arcilla Opalina como almacenamiento geológico profundo de residuos.

Keywords sedimentary rocks · waste disposal · hydrochemistry · Switzerland · confining units

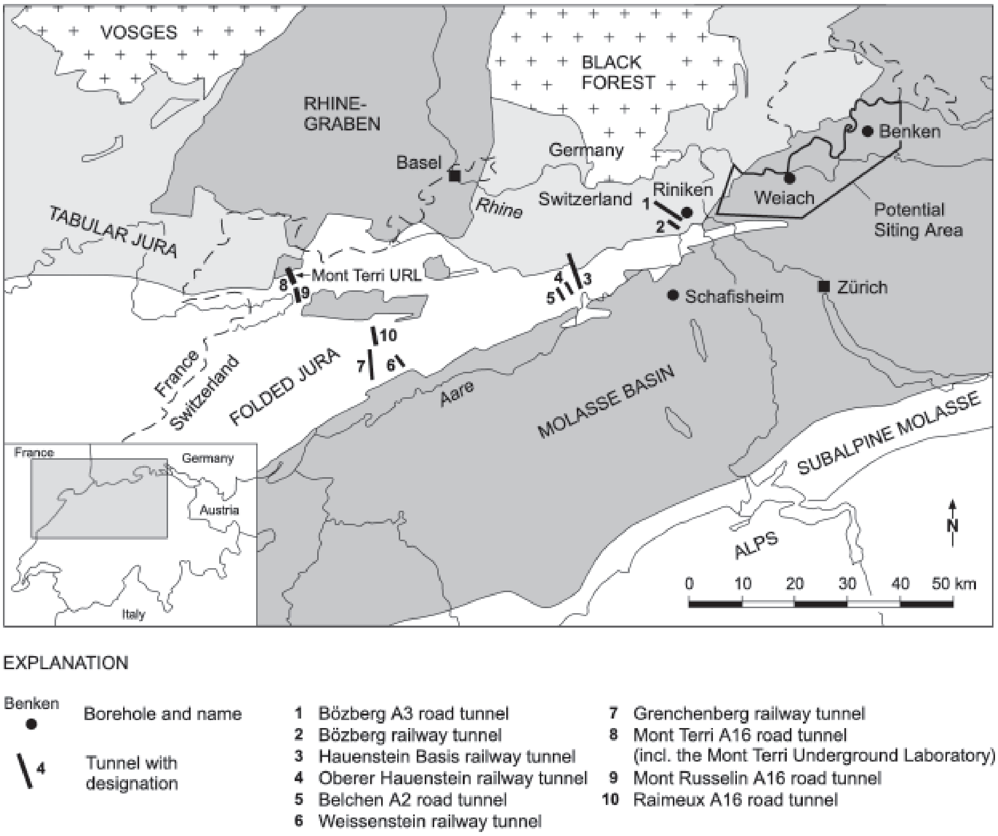
Introduction

As part of the Swiss programme for high-level radioactive-waste disposal, the National Cooperative for the Disposal of Radioactive Waste (Nagra) is currently investigating the Jurassic (Aalenian) Opalinus Clay as a potential host formation (Nagra 1988, 1994). The formation – named after the ammonite *Leioceras opalinum* – consists of indurated dark grey micaceous claystones (shales) that are subdivided into several lithostratigraphic units. Some of them contain thin sandy lenses, limestone concretions, or siderite nodules. The clay-mineral content ranges from 40–80 wt% (9–29% illite, 3–10% chlorite, 6–20% kaolinite, and 4–12% illite/smectite mixed layers in the ratio 70/30). Other minerals are quartz (15–30%), calcite (6–40%), siderite (2–3%), ankerite (0–3%), feldspars (1–7 %), pyrite (1–3 %), and organic carbon (<1%). The total water content ranges from 4–19% (Waber et al. 1998; Mazurek 1999). Faults are mainly represented by fault gouge and fault breccias, partly associated with minor veins of calcite with or without quartz and occasionally celestite (with widths mostly in the millimetre range, and rarely >1 cm; Waber and Schürch 1999).

The first studies of the Opalinus Clay carried out by Nagra date back to the end of the 1980s (Nagra 1988) and include results from earlier deep boreholes drilled as part of Nagra's crystalline-rock programme. Although the investigations in these boreholes focused on the crystalline basement, the sedimentary cover (including the Opalinus Clay) overlying the basement was also studied in detail in the Riniken, Schafisheim, and Weiach boreholes; locations are shown in Fig. 1. Based on the results of various two-dimensional reflection seismic surveys (Naef et al. 1995), a potential siting region for a repository for high-level and long-lived intermediate-level waste was then identified in northeastern Switzerland (Nagra 1994). As shown by the results of a recent three-dimensional seismic survey (Birkhäuser et al. 2000) and a deep borehole at Benken (Nagra in press), the Opalinus Clay occurs in this region as a 100–120-m-thick subhorizontal layer in a nearly undisturbed tectonic setting.

Numerous field and laboratory experiments in Opalinus Clay are being carried out in the Mont Terri Underground Laboratory in northwestern Switzerland. The experiments started in 1996 within the framework of an international research project[1] focusing on issues of radio-

Fig. 1 Major geotectonic units of northern Switzerland and vicinity showing study sites for Opalinus Clay



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[1] This research programme is under the patronage of the Swiss National Hydrological and Geological Survey. The following organisations are partners in the project: ANDRA and IPSN (France), BGR (Germany), ENRESA (Spain), NAGRA (Switzerland); JNC and OBAYASHI (Japan), SCK·CEN (Belgium).

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active-waste disposal in argillaceous rocks (Thury and Bossart 1999). The main aims are to test, develop, and improve investigative techniques for the hydraulic, geochemical, and rock-mechanical characterisation of argillaceous formations, as exemplified by the Opalinus Clay; to increase understanding of fluid flow and radionuclide migration processes; and to improve the understanding of coupled phenomena taking place in such host rocks. For Nagra, these investigations serve to complement the investigations carried out in the potential siting region.

The objectives of this paper are: (1) to present a comprehensive review of all relevant hydrogeological and geochemical information on the Opalinus Clay; (2) based on this information, to develop a conceptual understanding of solute transport in this potential host rock for nuclear waste; and (3) to build confidence in the conclusions by demonstrating consistency of results based on independent evidence obtained from studies of hydrochemistry and isotope hydrogeology.

Hydraulic Properties

Near-Surface Investigations

Phenomena observed in clay pits of northern Switzerland (Mazurek et al. 1996) and southern Germany (Hekel 1994) show evidence of a well-developed groundwater circulation system in the near-surface Opalinus Clay. In the uppermost 10–15 m, joint and fault systems have oxidation rims with thicknesses of several centimetres, and gypsum occurs on fracture surfaces.

As part of a German research project focused on investigating various aspects of hazardous waste disposal (Geologisches Landesamt Baden-Württemberg 1992), studies have been carried out in the Opalinus Clay of the Swabian Alb of southern Germany (about 50–150 km northeast of the region shown in Fig. 1). A wide variety of hydraulic tests, accompanied by core analyses, was performed in 47 shallow boreholes (Hekel 1994). Example results are shown in Fig. 2. The results show a consistent picture, with an upper section (10–30 m depth) with relatively high hydraulic conductivities ranging from 10^{-7}–10^{-4} m/s. This upper section contains numerous subvertical and horizontal fractures caused or reactivated by stress release due to erosion of the overlying strata. At 10–30 m depth, the hydraulic conductivity decreases by several orders of magnitude (Fig. 2) and, in one borehole, saline waters occur at a depth of 50 m, suggesting little or no advective flow there. Hydraulic conductivity and chloride content correlate inversely. The thickness of the highly permeable upper domain is closely related to the geomorphological evolution and topographic relief at the particular sites: thicker zones of chemical and mechanical alteration (as much as 30 m thick) are developed beneath old valleys and topographic ridges, whereas thinner zones generally occur below geologically young valley systems (Hekel 1994).

Hydraulic Testing in Deep Boreholes

Hydraulic tests in the Opalinus Clay and adjacent rock formations performed in 1983/84 in three Nagra deep

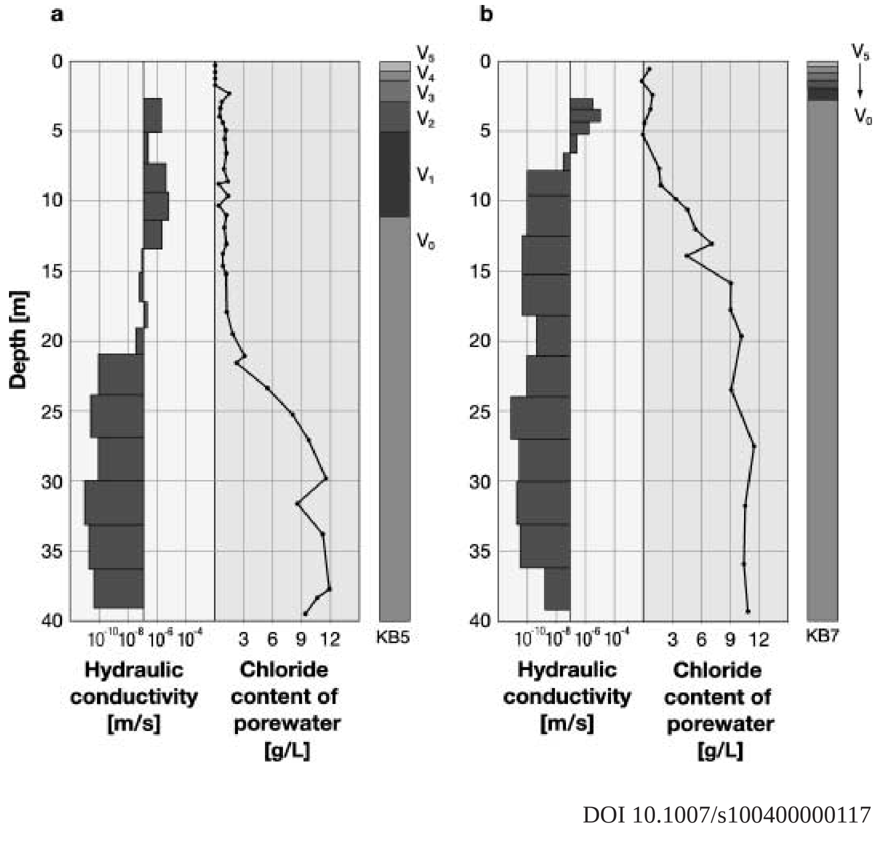

Fig. 2 Typical profiles of hydraulic conductivity of near-surface Opalinus Clay, and chloride concentration in pore water (data from leaching experiments). Data are from boreholes **a** KB5 and **b** KB7, at the Mössingen test site, Swabian Alb, Germany (Hekel 1994). Zones V5 to V0 are weathering zones after Einsele (1983) and Wetzel and Einsele (1991)

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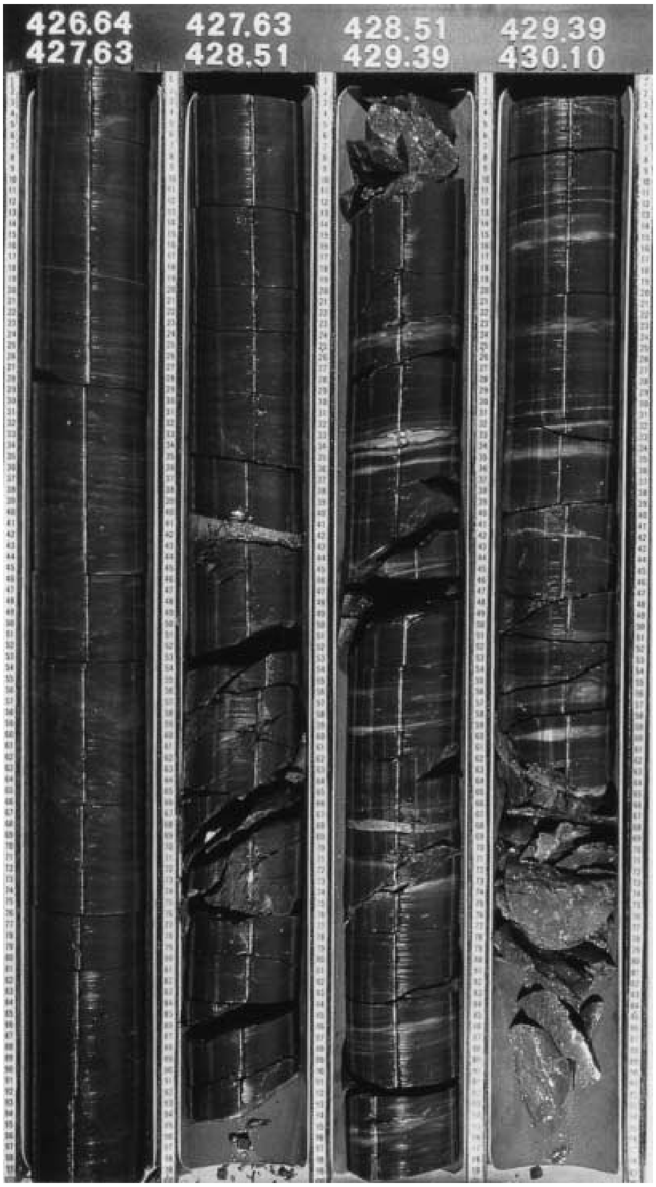

Fig. 3 Fault zone including shear zones and joints in the Opalinus Clay of the Riniken borehole (Fig. 1) (depth approx. 426–430 m). The hydraulic conductivity of the test section 398–430 m is 3×10^{-13}–2×10^{-14} m/s (Johns and Guyonnet 1993)

boreholes in northern Switzerland were (re)analysed in detail (Johns and Guyonnet 1993; Johns et al. 1994). The programme consisted of open-hole single and double packer tests at depth ranges (for the Opalinus Clay) of 330–450 m in the Riniken borehole (Belanger et al. 1989); of 560–670 m at Weiach (Butler et al. 1989); and of 1,000–1,080 m at Schafisheim (Moe et al. 1990). Fault zones were included in some of the test intervals, and an example is shown in Fig. 3. All tests in the Opalinus Clay yielded very low hydraulic conductivities, ranging from 10^{-14}–10^{-12} m/s. Extensive hydraulic testing was performed in the Benken borehole (drilled in 1998/99), where rocks in Opalinus Clay facies occur at 540–650 m. Standard interpretations of these tests confirm the very low permeability of the formation and provide evidence for porewater overpressures (Nagra, in press). Currently, more detailed analyses of the tests are being performed in order to assess the possibility of the overpressures being artefacts caused by non-hydraulic processes (e.g., borehole convergence).

Hydraulic Testing in Tunnels

In the Mont Terri Underground Laboratory, a large number of hydraulic tests and gas threshold pressure tests in short (<30 m) boreholes drilled from the tunnel have been carried out (various chapters in Thury and Bossart 1999). All test sections are at least 200 m below the surface. In addition, water-inflow rates from long-term pore-water sampling in upwardly drilled boreholes have been interpreted. All data suggest that the hydraulic conductivity of the Opalinus Clay outside the excavation disturbed zone around the tunnel is less than 10^{-12} m/s. Faults (mainly thrust faults) were also tested, but no indications of increased permeabilities were observed.

Hydrogeological Mapping of Tunnels

Hydrogeological information from Opalinus Clay sections of five railway tunnels and five motorway tunnels in the Folded Jura of northern Switzerland is presented in Gautschi (1994, 1997) and summarised in Table 1. The tunnels were constructed between 1860 and 1996. Most of the data originate from the exploration and excavation phases, with additional input from later repair and maintenance activities. The detection limit for a visual identification of damp patches along faults in ventilated tunnels has been assessed by Eugster and Senger (1994). Faults with transmissivities less than approximately 10^{-9} m^2/s cannot be detected under these circumstances.

The quality of the data, i.e., the degree of detail of the hydrogeological mapping, ranges from general descriptions of major water inflows, such as shown in Fig. 4, to detailed mapping of seepages and damp patches, such as shown in Fig. 5. The Opalinus Clay sections in the tunnels are located at depths of 100–800 m below surface. Despite the complex tectonics of the Folded Jura, comprising numerous faults in a water-saturated environment, only two damp patches and three measurable water inflows are reported for a total of 6,600 m of tunnel section in the Opalinus Clay. All these indications of water flow come from sections with little overburden (less than 200 m) and are either associated with an intercalated series of fractured calcareous sandstone layers – a facies that is developed only in the northwestern part of Switzerland – or with faults, some with minor calcite veins.

Evidence of Osmotic Flow

Evidence exists in the literature (e.g., Neuzil 2000) that very low permeability argillaceous rocks can act as a semi-permeable membrane capable of supporting an os-

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Table 1 Hydrogeological information from Opalinus Clay sections of tunnels in the Folded Jura, Switzerland (modified from Gautschi 1997). For location of tunnels, see Fig. 1

Tunnel and year of construction	Observed section in the Opalinus Clay	Thickness of overburden (m)	Hydrogeological mapping[a]	Characterisation of water flow, degree of rock deformation	References[b]
Bözberg A3 road tunnel (1991)	200 m (west tunnel), 120 m (east tunnel)	120	C (following installation of precast liners)	No indication of water during construction; one damp patch at gap between liner elements in tunnel after one year. Opalinus Clay partly strongly tectonised	1
Bözberg railway tunnel (around 1874)	130 m	200	None (new mapping: B)	No water inflows. Opalinus Clay less strongly tectonised than in road tunnel	1
Hauenstein Basis railway tunnel (1914)	120 m	300–400	A to B	No water inflows. Opalinus Clay less disturbed, dipping with an angle of approx. 45°	2
Oberer Hauenstein railway tunnel (around 1860)	150 m (tunnel), 100 m (shaft)	180	A (new mapping: B)	No water inflows. Opalinus Clay less disturbed, dipping with an angle of approx. 30°	1, 3, 4
Belchen A2 road tunnel (1965)	Four times 500 m (4 parallel pilot tunnels, 2 each in east and west tunnels; no data for main tunnel)	100–300	C	One damp patch in fracture zone with calcite. Opalinus Clay generally strongly tectonised and imbricated. Overburden<150 m	5
Weissenstein railway tunnel (1907)	375 m	400–500	B	No water inflows. Opalinus Clay strongly disturbed, generally steeply dipping (core of two anticlines)	6
Grenchenberg railway tunnel (1914)	350 m	700–800	A	No water inflows. Opalinus Clay strongly disturbed, generally steeply dipping (core of anticline)	7, 8
Mont Terri A16 road tunnel (1991)	South: 3 times 240 m (reconnaissance and pilot tunnel, main tunnel in axis of pilot tunnel)	300 m	C (main tunnel: B)	No indication of water inflows. Opalinus Clay slightly disturbed, dipping with an angle of approx. 30° (southern limb of anticline)	9, 10, 11
	North: 3 times 140 m (ventilation and transport tunnel, main tunnel in axis of transport tunnel)	150–200	C (main tunnel: B)	Two drip points in limy-sandy intercalation. Opalinus Clay strongly tectonised, imbricated (overthrust northern limb of anticline)	11, 12
Mont Russelin A16 road tunnel (1991)	Two times 1,100 m (pilot tunnel and main tunnel, around 40 m beside pilot tunnel)	300–400	C (main tunnel: A to B)	No indication of water inflows. Opalinus Clay generally strongly tectonised and imbricated (core of anticline)	13, 14, 15
Raimeux A16 road tunnel (1996)	240 m (reconnaissance tunnel)	120–140	B to C	One drip point in clayey facies; one water inflow in calcareous facies (NaCl-rich water). Opalinus Clay subvertical, strongly tectonised	16

[a] Degree of detail of hydrogeological mapping: *A* only marked water inflows (springs), *B* all springs and tunnel sections with drip points, *C* all indications of water inflow (including damp patches)

[b] References: *1* Wegmüller (1991–1993), *2* Wiesmann (1917), *3* Anonymous (around 1860) Geological profile of the Hauenstein tunnel 1:25,000. Dr. H. Schmassmann, Liestal (private archives), *4* Watson (around 1860) 'Profil des Hauensteintunnels'. Dr. H. Schmassmann, Liestal (private archives), *5* Fröhlicher (1966), *6* Buxtorf et al. (1908), *7* Buxtorf and Trösch (1917), *8* Berner-Alpenbahn-Gesellschaft Bern–Lötschberg–Simplon (1917), *9* Bureaux Geologiques Associés Norbert and Schindler (1990), *10* Bureau Schindler (1991), *11* Bureau Technique Norbert (1992a), *12* R. Haarpaintner (Bureau Technique Norbert), personal communication 1993, *13* Bureau Technique Norbert (1992b), *14* Bureau Technique Norbert (1992c), *15* CMR (1990–1991), *16* MFR Géologie–Géotechnique S.A. Biel, Switzerland 1996, personal information (photocopy of hydrogeological tunnel profile with hand-written notes)

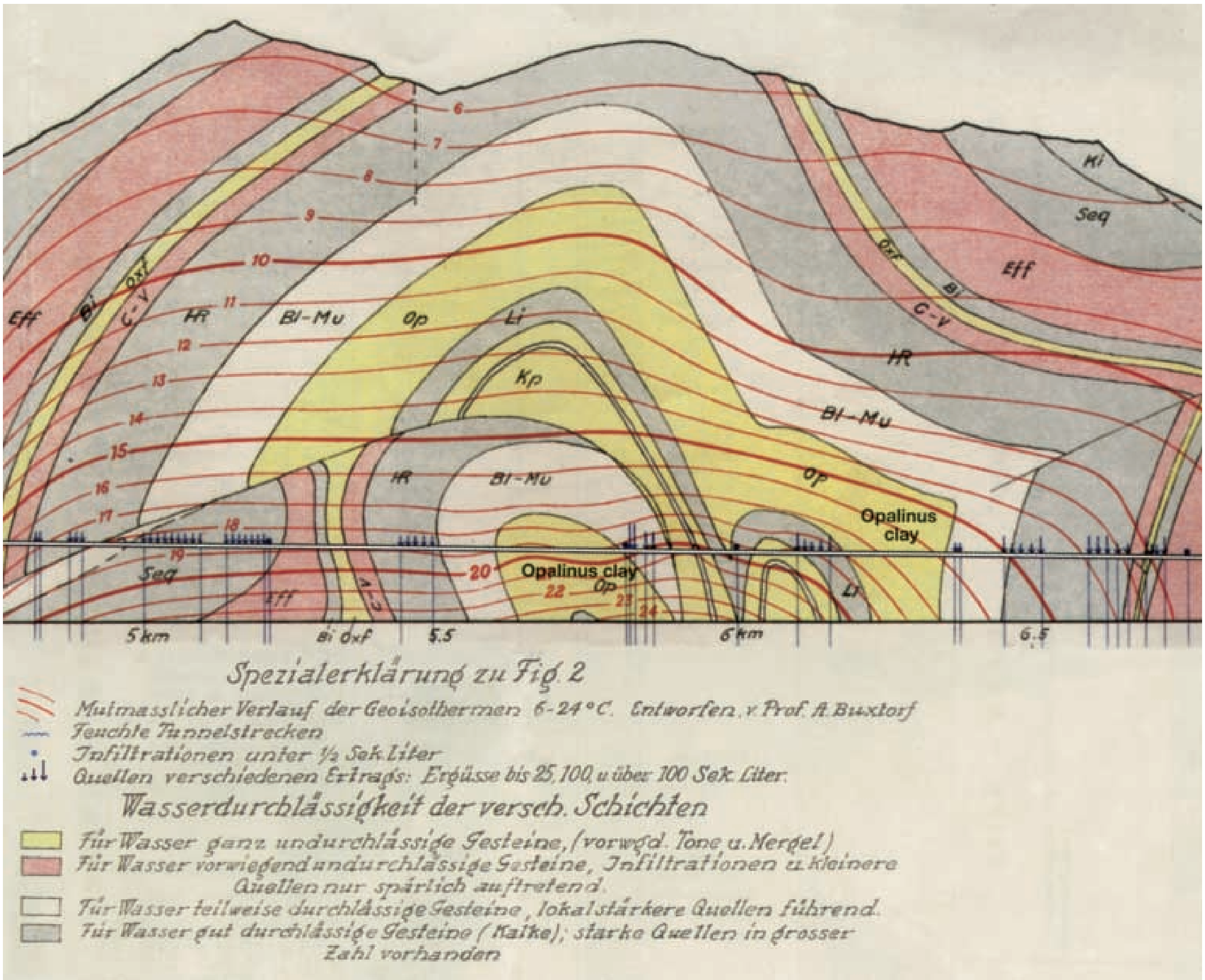

Fig. 4 Hydrogeological information from the Grenchenberg tunnel (Fig. 1, no. 7). Facsimile reproduction from Buxtorf and Trösch (1917). The rock units are characterised in terms of their permeability: *yellow* rocks practically impermeable to water, *red* rocks with only rare occurrences of infiltrations and small springs, *grey* and *white* rocks with moderate to good hydraulic conductivity, *blue arrow* and *dot* spring encountered during tunnel construction, *blue wavy line* damp section (only outside the section shown here). The Opalinus Clay tunnel sections (around 400 m) were dry. *Red line* presumed trend of the isotherms (in °C)

motic flow of pore water. This flow may have an impact on the interpretation of hydraulic tests in argillaceous rocks (borehole-fluid effects), as well as on the interpretation of formation pressures in sedimentary basins. Harrington and Horseman (1999, 2000) performed laboratory experiments on 1-cm-thick slices of Opalinus Clay from Mont Terri under confining pressure. A steady-state osmotic pore-water flow was established, but the osmotic efficiency of the Opalinus Clay membrane was rather low (6–10%). Currently, a single-borehole field experiment based on a sequential exchange of borehole fluids with different salinities is being carried out in the Mont Terri Underground Laboratory in order to quantify the osmotic efficiency under in situ conditions.

Geochemistry of Groundwaters and Pore Waters

A set of data on the chemical composition of near-surface waters in the Opalinus Clay is presented in Hekel (1994). These data include the results of chemical analyses and isotope measurements (deuterium, oxygen-18, tritium) on more than 60 water samples from shallow boreholes and clay pits, as well as chloride concentrations in pore water from Opalinus Clay samples (leaching and squeezing tests). Results from pore water and fracture water from greater depths are available from the Mont Terri Project (Gautschi et al. 1993; Pearson et al. 1999; Rübel et al. 1999; Rübel 2000) and the Benken deep borehole (Nagra, in press). These ongoing investi-

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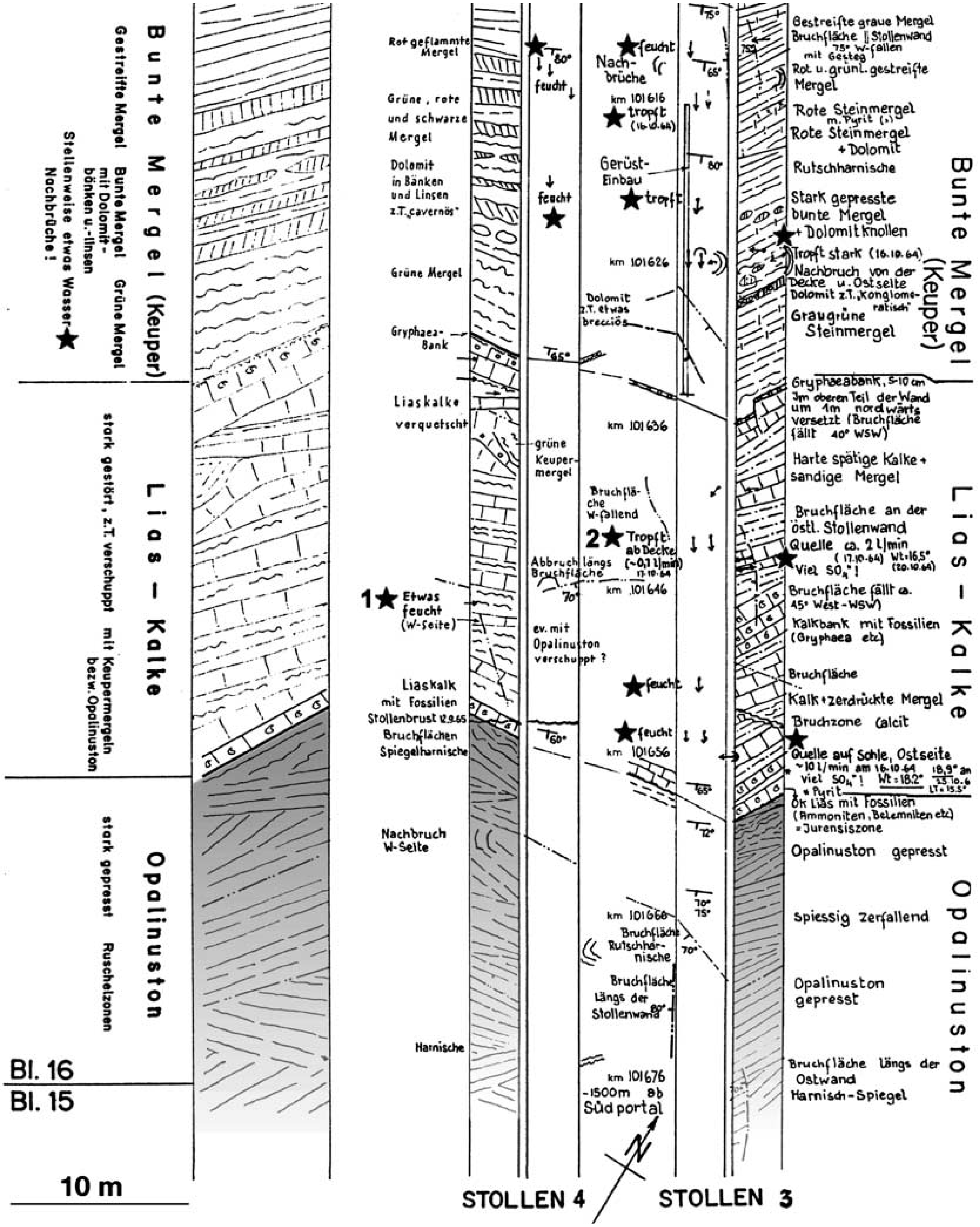
Fig. 5 Example of hydrogeological mapping of the exploration drifts 3 and 4 for the Belchen A2 motorway tunnel (Fig. 1, no. 5). Facsimile reproduction from Fröhlicher (1966). The section shows the uppermost part of the Triassic rocks, the Liassic rocks, and the lowest part of the Opalinus Clay. *Star* Damp patch and water inflow observed outside the Opalinus Clay; for example: *1* slightly damp; *2* dripping from ceiling, 0.1 L/min. Each of the total of four exploration drifts crosscuts 500 m of strongly faulted Opalinus Clay, but only one damp patch (associated with a fault containing calcite veins, not shown in the figure) was encountered in the Opalinus Clay


Bunte Mergel (Keuper)
Gestreifte Mergel
Bunte Mergel mit Dolomit-bänken u.-linsen
Grüne Mergel
Stellenweise etwas Wasser
Nachbrüche !
Lias – Kalke
stark gestört, z.T. verschuppt mit Keupermergeln bezw. Opalinuston
Opalinuston
stark gepresst Ruschelzonen
Bl. 16
Bl. 15
10 m
Rot geflammte Mergel
Grüne, rote und schwarze Mergel
Dolomit in Bänken und Linsen z.T. „cavernös"
Grüne Mergel
Gryphaea-Bank
Liaskalke verquetscht
grüne Keupermergel
1 Etwas feucht (W-Seite)
Liaskalk mit Fossilien
Stollenbrust 12.9.65
Bruchflächen Spiegelharnische
Nachbruch W-Seite
Harnische
80°
feucht
feucht
65°
60°
Abbruch längs Bruchfläche
70°
ev. mit Opalinuston verschuppt ?
feucht
Nachbrüche
km 101616
tropft (16.10.64)
Gerüst-Einbau
tropft
km 101626
Dolomit z.T. etwas brecciös
km 101636
Bruchfläche W-fallend
2 Tropft ab Decke (~0,1 l/min) 17.10.64
km 101646
feucht
feucht
km 101656
km 101666
Bruchfläche Rutschharnische
Bruchfläche längs der Stollenwand
km 101676
-1500m ab Südportal
75°
65°
80°
65°
72°
70°
75°
70°
80°
75°
Gestreifte graue Mergel
Bruchfläche ‖ Stollenwand 75° W-fallen mit Gesteg
Rot u. grünl. gestreifte Mergel
Rote Steinmergel m. Pyrit (.)
Rote Steinmergel + Dolomit
Rutschharnische
Stark gepresste bunte Mergel + Dolomitknollen
Tropft stark (16.10.64)
Nachbruch von der Decke u. Ostseite
Dolomit z.T. „konglomeratisch"
Graugrüne Steinmergel
Bunte Mergel (Keuper)
Gryphaeabank, 5-10 cm
Im oberen Teil der Wand um 1m nordwärts versetzt (Bruchfläche fällt 40° WSW)
Harte spätige Kalke + sandige Mergel
Bruchfläche an der östl. Stollenwand
Quelle ca. 2 l/min (17.10.64) Wt=16,5° (20.10.64)
Viel SO_4"!
Bruchfläche fällt ca. 45° West-WSW)
Kalkbank mit Fossilien (Gryphaea etc)
Bruchfläche
Kalk + zerdrückte Mergel
Bruchzone Calcit
Quelle auf Sohle, Ostseite ~10 l/min am 16.10.64
Viel SO_4"! Wt=18.2° 18,9° an 23.10.6 LT=15.5°
+ Pyrit
OK Lias mit Fossilien (Ammoniten, Belemniten etc) = Jurensiszone
Opalinuston gepresst
Spiessig zerfallend
Opalinuston gepresst
Bruchfläche längs der Ostwand Harnisch-Spiegel
Lias – Kalke
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N
STOLLEN 4
STOLLEN 3

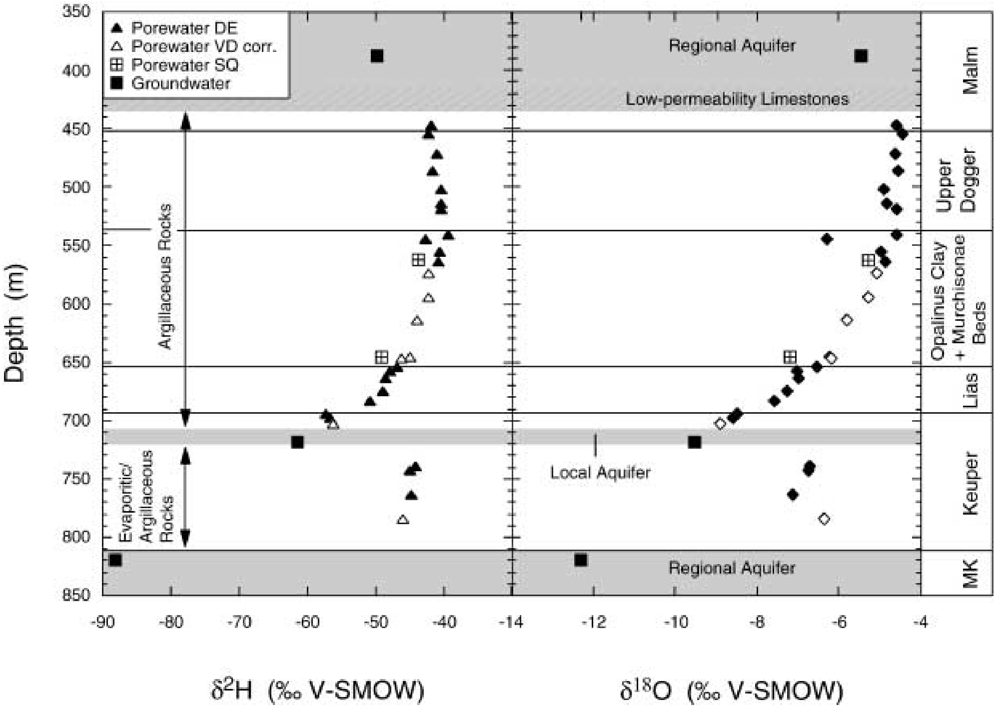

Fig. 6 δ^2H and δ^{18}O profiles in the Benken borehole, northern Switzerland (Fig. 1), based on pore water extracted by several methods (data from Rübel and Sonntag 2000; Nagra, in press). Pore water extraction methods: *DE* diffusive equilibration, *VD corr*. vacuum distillation corrected for incomplete distillation, *SQ* high-pressure squeezing. *MK* Muschelkalk aquifer

gations, which use and compare various pore-water extraction methods, will yield additional geochemical and isotopic data (F.J. Pearson, New Bern, NC, USA, personal communication 2000; A. Bath, Willoughby-on-the-Wolds, UK, personal communication 2000).

The chemistry of the near-surface waters shows a marked depth zonation, which correlates with the distribution of hydraulic properties described above. The uppermost water contains tritium and is of the Ca–Mg–SO_4–HCO_3 type. This water is part of a shallow fractured groundwater circulation system with a relatively short underground residence time (<40 years). Its chemistry reflects the geochemical weathering of the Opalinus Clay: carbonate dissolution and oxidation of pyrite and siderite first cause precipitation of iron hydroxides and gypsum, followed by subsequent gypsum dissolution during the evolution of the oxidation front, which propagates along the fracture system present at shallow depths. With increasing underground residence time, calcium–sodium ion-exchange processes become more important and near-surface water gradually evolves into tritium-poor Na–HCO_3–(SO_4–Cl) water. At 10–30 m depth, a pronounced increase in salinity (Fig. 2) indicates the transition to a zone of quasi-stagnant pore water, where diffusion becomes the dominant mechanism for solute transport. The pore water is of Na–Cl–SO_4 type and has a salinity (total dissolved solids) of 10–20 g/L, δ^2H and δ^{18}O values higher than values for recent recharge, and (at Mont Terri) a chloride/bromide ratio similar to that of seawater (Pearson et al. 1999). However, the major-element composition of the pore water, the hydrogen- and oxygen-isotope ratios of water, and the chlorine-37/35 ratios cannot be reconciled with simple seawater–meteoric–water mixing processes (Pearson et al. 1999). The pore-water composition rather reflects a complex series of processes comprising pore-water expulsion during compaction, in- and out-diffusion of various components during two subsequent burial/uplift phases, and water–rock interaction.

Helium accumulates in the Opalinus Clay pore water by in situ production from α-decay of U and Th in the rock. Simultaneously, helium is depleted by out-diffusion into adjacent aquifers. ^{4}He concentration in the pore water was measured using a vacuum extraction technique on core samples. The highest values are about 10^{-4} cm^3 ^{4}He/cm^3 H_2O. Taking into account mean U and Th concentrations in the rock, a release efficiency of 1 (100%) and an average water content, Rübel et al. (1999) calculated a minimum residence time of ^{4}He in the formation to be about 10 m.y.

Current geochemical investigations on the Opalinus Clay and adjacent aquifers at Mont Terri and Benken provide large-scale profiles of various pore-water components (chloride, δ^2H and δ^{18}O of water, ^{4}He, and δ^{37}Cl) across the formation. Strong evidence exists that diffusion is the major process governing solute transport in the Opalinus Clay (Rübel 2000; Rübel and Sonntag 2000; Nagra, in press; A. Bath, Willoughby-on-the-Wolds, UK, personal communication 2000; M. Coleman, University of Reading, UK, personal communication 1999). An example of a profile from the Benken borehole is shown in Fig. 6. In a δ^2H–δ^{18}O diagram (Rübel and Sonntag 2000, not shown here), the isotopic composition of waters in the Malm aquifer and in the upper part of the argillaceous rocks plot on the right hand side of the Global Meteoric Water Line, indicating that they are altered connate waters. δ^2H and δ^{18}O values decrease in the lower part of the Opalinus Clay and in the Lias, and plot on the Global Meteoric Water Line, suggesting in-diffusion of meteoric water from the Keuper aquifer. Numerical simulations of the profile (T. Gimmi, University of Bern, Switzerland, personal communication 2000) suggest diffusion times on the order of 1 million years. Pore waters in the vicinity of a tight minor fault that was penetrated at a depth of 602 m indicate no geochemical anomalies.

Faults that are acting or have acted as preferential pathways can probably be identified by anomalies in the hydrochemical or isotopic signature of the formation. Although some of the pore-water samples in the studies referenced above derive from faulted test intervals or from cores of faults or the nearby vicinity, no hydrochemical or isotopic anomalies have been identified in the Opalinus Clay.

Implications for Radionuclide Transport

Retardation Processes in Fractured Rocks

In fractured rock, water flow occurs predominantly in the discontinuities (joints, faults). When investigating the transport of dissolved radionuclides, it is also important to consider the possibility of nuclide diffusion from such flowpaths into the connected pore structure of the surrounding rock matrix (e.g., Grisak and Pickens 1980; Neretnieks 1980). Such ‘matrix diffusion’ not only increases the area of mineral surfaces that is available for radionuclide sorption, but it also provides a volume of dead space where even non-sorbing radionuclides can be significantly retarded in stagnant pore water (e.g., Hadermann and Roesel 1985).

Potential features that could decrease the effectiveness of radionuclide retardation are (1) the existence of preferential pathways (channels) within the discontinuities (reduction of the volume of rock in contact with flowing groundwater); (2) sealing of fracture surfaces by non-sorbing, non-porous mineral coatings (radionuclides are denied access to the rock matrix); and (3) high fracture transmissivities (radionuclides have insufficient time to diffuse into the rock matrix).

Discussion of Observations

Investigations in near-surface Opalinus Clay demonstrate that advective fracture flow and matrix diffusion are the dominant processes at shallow depths (Hekel 1994; Mazurek et al. 1996). The extensive data available indicate that these fractures are permeable due to surface-related decompression and weathering effects. On the other hand, the large number of faults and joints penetrated in deep boreholes and in a total of 6,600 m of tunnels revealed only five indications of minor seepage, all of which are associated with zones with a relatively small overburden. All these field observations lead to a conceptual model of a strong depth dependence of the permeability of the Opalinus Clay, which is also represented by a marked hydrochemical depth zonation. Furthermore, independent evidence also exists from hydrochemical and isotopic data that (1) the underground residence time of pore water at large depths is on the order of millions of years; (2) as a rule, faults do not represent preferential pathways for advective flow; and (3) diffusion is the most important solute-transport process. Furthermore, no indications exist of narrow flow channels, like those observed in crystalline rocks of northern Switzerland (Thury et al. 1994; Gautschi 1995; Mazurek 2000; Mazurek et al. 2000). The presence of minor calcite and celestite veinlets in some of the discontinuities (Waber and Schürch 1999) is the only suggestion of possible fracture coatings.

Conclusions

The extensive hydraulic database – part of which derives from particularly unfavourable (from a waste-disposal point of view), strongly faulted geological environments – provides arguments that advective transport through faults and joints is not a critical issue for the suitability of Opalinus Clay as a host rock for deep geological disposal of radioactive wastes. This conclusion is also supported by independent evidence from clay pore-water hydrochemical and isotopic data. At least for a large part of the deep Opalinus Clay, diffusion through the bulk rock mass would be the dominant process for radionuclide transport. Preliminary simple safety analyses (Nagra 1988) demonstrate that in this case even a few tens of metres of good rock would provide an extremely efficient transport barrier for all radionuclides. A full safety case (total system performance assessment) on the Opalinus Clay is in preparation and publication is planned by the end of 2002.

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References

Belanger DW, Cauffman TL, Lolcama JL, Longsine DE, Pickens JF (1989) Interpretation of hydraulic testing in the sediments of the Riniken Borehole. Nagra Technical Report NTB 87–17, Nagra, Wettingen, Switzerland

Berner-Alpenbahn-Gesellschaft Bern–Lötschberg–Simplon (1917) Bau der normalspurigen Hauptlinie Münster–Lengnau (Grenchenbergtunnel 8578 m) [Bernese Alpine Railway Company, Bern–Lötschberg–Simplon, construction of the normal gauge main line Münster–Lengnau (Grenchenberg tunnel 8578 m)]. Final report, published by the author

Birkhäuser P, Müller WH, Roth P, Näf H (2000) 3D seismic survey Zürcher Weinland: processing and interpretation. Nagra Bull 33:18–29

Bureau Schindler (1991) Etude géologique et hydrogéologique des Marnes Aaléniennes du Mt. Terri – rapport complémentaire [Geological and hydrogeological investigation of the Opalinus Clay at Mont Terri – complementary report]. Nagra Internal Report, Nagra, Wettingen, Switzerland

Bureau Technique Norbert (1992a) Tunnel du Mont Terri – profil en long géologique 1:5000 (prévision/exécution) [Mont Terri tunnel – geological cross-section 1:5000 (prediction/findings)]. Bureau Technique Norbert, Lausanne/St-Ursanne, Switzerland

Bureau Technique Norbert (1992b) Tunnel du Mont Russelin – profil en long géologique 1:5000 (prévision/exécution) [Mont Russelin tunnel – geological cross-section 1:5000 (prediction/findings)]. Bureau Technique Norbert, Lausanne/St-Ursanne, Switzerland

Bureau Technique Norbert (1992c) Marnes Aaléniennes – etude géologique et hydrogéologique dans la galerie pilote du Mont Russelin [Geological and hydrogeological investigations in the Mont Russelin pilot tunnel]. Nagra Internal Report, Nagra, Wettingen, Switzerland

Bureaux Géologiques Associés Norbert et Schindler (1990) Etude géologique et hydrogéologique des Marnes Aaléniennes (Opalinuston) dans la galerie de reconnaissance du Mt. Terri (N16-Transjurane) [Geological and hydrogeological investigation of the Opalinus Clay in the reconnaissance gallery at Mont Terri (N 16-Transjurane)]. Nagra Internal Report, Nagra, Wettingen, Switzerland

Butler GA, Cauffman TL, Lolcama JL, Longsine DE, McNeish JA (1989) Interpretation of hydraulic testing at the Weiach Borehole. Nagra Technical Report NTB 87–20, Nagra, Wettingen, Switzerland

Buxtorf A, Trösch A (1917) Geologie des Grenchenbergs mit Berücksichtigung der hydrographischen und thermischen Verhältnisse und der Tunnelbeben. Separatabdruck aus dem Schlussbericht an das schweizerische Post- und Eisenbahndepartement über den Bau der normalspurigen Hauptlinie Münster-Lengnau (Grenchenbergtunnel 8578 m) [Geology of the Grenchenberg, taking into account hydrographic and thermal conditions, and earthquakes. Separate reprint from the final report of the Swiss Post and Railways Department on construction of the normal gauge main line Münster–Lengnau (Grenchenberg tunnel 8578 m)]. Berner-Alpenbahn-Gesellschaft Bern–Lötschberg–Simplon

Buxtorf A, Kuenzli E, Rollier L (1908) Geologische Beschreibung des Weissensteintunnels und seiner Umgebung [Geological description of the Weissenstein tunnel and its vicinity]. Beiträge zur geologischen Karte der Schweiz (Neue Folge), Lieferung 21

CMR (Consortium d'étude Mont Russelin) (1990–1991) Tunnel du Mont Russelin – Galerie pilote – Relevé géologique 1:100 [Mont Russelin tunnel – pilot tunnel – geological map 1:100]. Bureau Technique Norbert, Lausanne/St-Ursanne, Switzerland

Einsele G (1983) Mechanismus und Tiefgang der Verwitterung bei mesozoischen Ton- und Mergelgesteinen [Mechanism and depth of weathering of Mesozoic clays and marls]. Z Dtsch Geol Ges 134:289–315 (in German, with figure captions in English)

Eugster S, Senger RK (1994) Nachweisgrenze von Transmissivität eines transmissiven Elements (TE) an der ventilierten Stollenwand [Detection limit of the transmissivity of a transmissive element (TE) on a ventilated tunnel wall]. Nagra Internal Report, Nagra, Wettingen, Switzerland

Fröhlicher H (1966) Nationalstrasse N2, Belchentunnel Süd, Tunnelröhren Ost und West, Geologische Aufnahmen 1:200 [National highway N2, Belchen tunnel south, east and west tunnels, geological mapping 1:200]. Schweizerische Geologische Dokumentationsstelle [Swiss Geological Documentation Office], Bern

Gautschi A (1994) Wasserführung des Opalinus-Tons in Tunnels des Faltenjuras [Water flow in the Opalinus Clay in tunnels in the Folded Jura]. Nagra Internal Report, Nagra, Wettingen, Switzerland

Gautschi A (1995) The crystalline programme: investigations, results, future procedure. Nagra Bull 25:10–21

Gautschi A (1997) Hydrogeology of the Opalinus Clay – implications for radionuclide transport. Nagra Bull 31:24–32

Gautschi A, Ross C, Scholtis A (1993) Porewater – groundwater relationships in Jurassic shales and limestones of northern Switzerland. In: Manning DAC, Hall PL, Hughes CR (eds) Geochemistry of clay–pore fluid interactions. Mineral Soc Ser 4. Chapman & Hall, London, pp 412–422

Geologisches Landesamt Baden-Württemberg (1992) Forschungsprojekt 'Gebirgseigenschaften mächtiger Tonsteinserien. Textband + Anlageband [Research project 'Properties of thick claystone series', text and appendices]. Geological Survey of Baden-Württemberg, Freiburg i. Br., Germany

Grisak GE, Pickens JF (1980) Solute transport through fractured media, Part I: the effect of matrix diffusion. Water Resour Res 16:719–730

Hadermann J, Roesel (1985) Radionuclide chain transport in inhomogeneous crystalline rocks – limited matrix diffusion and effective surface sorption. Nagra Technical Report NTB 85–40, Nagra, Wettingen, Switzerland

Harrington JF, Horseman ST (1999) Laboratory experiments on hydraulic and osmotic flow. In: Thury M, Bossart P (eds) Mont Terri Rock Laboratory: results of the hydrogeological, geochemical and geotechnical experiments performed in 1996 and 1997. Geological Reports No. 23, Swiss National Hydrological and Geological Survey, Bern pp 60–64

Harrington JF, Horseman ST (2000) Laboratory experiments on hydraulic and osmotic flow in Opalinus Clay. Mont Terri Project, Technical Report 2000–01, Swiss National Hydrological and Geological Survey, Bern

Hekel U (1994) Hydrogeologische Erkundung am Beispiel des Opalinustons (Unteres Aalenium) [Hydrogeological investigation of the Opalinus Clay (Lower Aalenian)]. Tübinger Geowiss Arbeiten C 18, University of Tübingen, Germany

Johns RT, Guyonnet D (1993) Interpretation of selected hydrotests in the Mesozoic sediments of the Nagra boreholes in northern Switzerland. Nagra Internal Report, Nagra, Wettingen, Switzerland

Johns RT, Vomvoris SG, Löw S (1994) Review of hydraulic field tests in the Opalinus Clay of Northern Switzerland. In: NEA (ed) Hydraulic and hydrochemical characterisation of argillaceous rocks. Proc Int Workshop, Nottingham (UK), 7–9 June 1994, OECD/NEA, Paris, pp 167–177

Mazurek M (1999) Mineralogy of the Opalinus Clay. In: Thury M, Bossart P (eds) Mont Terri Rock Laboratory: results of the hydrogeological, geochemical and geotechnical experiments performed in 1996 and 1997. Geological Reports No. 23, Swiss National Hydrological and Geological Survey, Bern, pp 15–18

Mazurek M (2000) Geological and hydraulic properties of water-conducting features in crystalline rocks. In: Stober I, Bucher K (eds) Hydrogeology in crystalline rocks. Kluwer Scientific, Dordrecht, pp 3–26

Mazurek M, Alexander WR, MacKenzie AB (1996) Contaminant retardation in fractured shales: matrix diffusion and redox front entrapment. J Contam Hydrol 21:71–84

Mazurek M, Gautschi A, Smith PA, Zuidema P (2000) The role of water-conducting features in the Swiss concept for the disposal of high-level radioactive waste. In: Stober I, Bucher K (eds) Hydrogeology in crystalline rocks. Kluwer Scientific, Dordrecht, pp 105–125

Moe H, McNeish JA, McCord JP, Andrews RW (1990) Interpretation of hydraulic testing at the Schafisheim borehole. Nagra Technical Report NTB 89–09, Nagra, Wettingen, Switzerland

Naef H, Birkhäuser P, Roth P (1995): Interpretation der Reflexionsseismik im Gebiet nördlich Lägern – Zürcher Weinland [Interpretation of reflection seismic measurements in the region northern Lägern – Zürcher Weinland]. Nagra Technical Report NTB 94–14, Nagra, Wettingen Switzerland

Nagra (1988) Sediment study – intermediate report 1988 – disposal options for long-lived radioactive waste in Swiss sedimentary formations – executive summary. Nagra Technical Report NTB 88–25E, Nagra, Wettingen, Switzerland

Nagra (1994) Sediment study – interim report 1993 (in German). Nagra Technical Report NTB 94–10. Nagra, Wettingen, Switzerland

Nagra (in press) Sondierbohrung Benken: Untersuchungsbericht [Benken borehole: investigation report]. Nagra Technical Report NTB 00–01 Nagra, Wettingen, Switzerland

Neretnieks I (1980) Diffusion in the rock matrix: an important factor in radionuclide retardation? J Geophys Res 85:4379–4397

Neuzil C (2000) Osmotic generation of ‘anomalous’ pressures in geological environments. Nature 403:182–184

Pearson FJ, Scholtis A, Gautschi A, Baeyens A, Bradbury M, Degueldre C (1999) Chemistry of porewater. In: Thury M, Bossart P (eds) Mont Terri Rock Laboratory: results of the hydrogeological, geochemical and geotechnical experiments performed in 1996 and 1997. Geological Reports No. 23. Swiss National Hydrological and Geological Survey, Bern, pp 127–147

Rübel A (2000) Stofftransport in undurchlässigen Gesteinen – Isotopenuntersuchungen im Grund- und Porenwasser [Material transport in impermeable rocks – isotopic studies in ground- and porewater]. PhD Thesis, Univ Heidelberg, Der Andre Verlag, Osnabrück, Germany

Rübel A, Sonntag C (2000) Sondierbohrung Benken: profiles of pore water content, stable isotopes and dissolved noble gas content in the pore water of samples from argillaceous rocks. Nagra Internal Report, Nagra, Wettingen, Switzerland

Rübel A, Lippmann J, Sonntag C (1999) Noble gases and isotopes from porewaters and rocks. In: Thury M, Bossart P (eds) Mont Terri Rock Laboratory: results of the hydrogeological, geochemical and geotechnical experiments performed in 1996 and 1997. Geological Reports No. 23. Swiss National Hydrological and Geological Survey, Bern, pp 148–151

Thury M, Bossart P (eds) (1999) Mont Terri Rock Laboratory: results of the hydrogeological, geochemical and geotechnical experiments performed in 1996 and 1997. Geological Reports No. 23, Swiss National Hydrological and Geological Survey, Bern

Thury M, Gautschi A, Mazurek M, Müller WH, Naef H, Pearson FJ, Vomvoris S, Wilson W (1994) Geology and hydrogeology of the crystalline basement of northern Switzerland – synthesis of regional investigations 1981–1993 within the Nagra radioactive waste disposal programme. Nagra Technical Report NTB 93–01, Nagra, Wettingen, Switzerland

Waber HN, Schürch R (1999) Opalinus Clay: fracture mineralogy and geochemistry as constraints on porewater composition. Nagra Internal Report, Nagra, Wettingen, Switzerland

Waber HN, Mazurek M, Pearson FJ (1998) Opalinus Clay: reference porewater, mineralogy and porosity: status April 1998. Nagra Internal Report, Nagra, Wettingen, Switzerland

Wegmüller M (1991–1993) Einflüsse des Bergwassers auf die verschiedenen Bauwerksteile des N3-Bözbergtunnels [Influence of groundwater on the different structural components of the N3 Bözberg tunnel]. Interim reports I, II, III (1991), IV, and V (1992) and final report (1993). Archives of Tiefbauamt of Canton Aargau. Also included in these reports are old and new data from the Bözberg railway tunnel and the Oberer Hauenstein railway tunnel

Wetzel A, Einsele G (1991) On the physical weathering of various mudrocks. Bull Int Assoc Eng Geol 44:89–100

Wiesmann E (1917) Der Bau des Hauenstein-Basistunnels Basel–Olten [Construction of the Hauenstein base tunnel Basel–Olten]. Julius Berger Tiefbau AG, Berlin

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