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Heterogeneous aquitard properties in sedimentary successions in the Apennine chain: case studies in southern Italy

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Abstract:

The aim of this study was to analyse the hydrogeologic role of siliciclastic deposits and marly-clayey-calcareous successions within the carbonate Apennine chain (southern Italy). The study was carried out along the northern part of the Matese carbonate massif through (1) the hydraulic characterization of siliciclastic rocks in a test site, by means of Lugeon tests, and (2) the identification of the groundwater flow system discharging at an important spring located within a marly-clayey-calcareous succession in a second test site, by means of isotopic investigations.

The results showed that the investigated siliciclastic deposits and marly-clayey-calcareous successions may allow significant groundwater discharge from carbonate aquifers. Thus, they do not everywhere behave as aquitard, contrary to the previous model. Instead, groundwater flows through the upper part of these successions, where stress release fracturing enhanced rock permeability in the near-surface bedrock. Thus, these successions may locally be a new groundwater source within the southern Apennine chain.

KEY WORDS aquitard; carbonate aquifer; marly-clayey-calcareous successionsiliciclastic deposits; southern Italy

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INTRODUCTION

Carbonate aquifers are a primary source of groundwater in southern Italy supplying an average volume of $4{\cdot}1 \times 10^9$ m^3 per year (Celico, 1983). Hydrogeologic surveys that were carried out mainly at regional or catchment scale suggested that the main springs of these aquifers often occur at the contact with lower permeability siliciclastic deposits or marly-clayey-calcareous successions. These successions are then considered as aquitards in the present conceptual model (Celico, 1986). Somewhere, the permeability contrast between carbonate massifs and the lower permeability rocks mentioned above is further emphasized by low-permeability tectonic discontinuities (Celico, 1986). Nevertheless, to date there are no studies at site scale that analyse relationships between carbonate aquifers and their relative aquitards, despite the possibility that these interactions may have a great significance in controlling the effectiveness of groundwater flow schemes and water balances in carbonate aquifers and in defining the potential of these lower permeability rocks as a groundwater source. The hydrogeologic role of other successions made up of sandstones, marls and siltstones have been recently investigated in northern Apennine (Italy). The research demonstrated that the latter does not behave as aquitard (Gargini *et al.*, 2008; Vincenzi *et al.*, 2009), as reported in previous studies. In such a case, the inaccurate interpretation of their hydrogeologic behaviour led to construction of new high-speed railway tunnels connecting Bologna and Firenze that drained an enormous volume of groundwater. For example, 2 years after completion of the 15-km-long Firenzuola tunnel, the average drainage outflow was $0{\cdot}35$ m^3 s^{-1} (Vincenzi *et al.*, 2009). A few other studies (Eaton and Bradbury, 2003; Eaton *et al.*, 2007) on the hydrogeology of sedimentary rock aquitards demonstrated that flow dynamics can be more complex than previously believed. The new findings have important implications for predicting groundwater flow and for planning and protecting water supplies.

The main goal of this research was to analyse the hydrogeologic role of siliciclastic deposits and marly-clayey-calcareous successions along the northern part of the Matese carbonate massif (southern Italy) through (1) the hydraulic characterization of siliciclastic rocks at a test site, by means of Lugeon tests and (2) the identification of the groundwater flow system discharging at an important spring located within a marly-clayey-calcareous succession at a second test site, by means of isotopic investigations.

STUDY AREA

The Matese carbonate massif (Figure 1) is an important drinking water source, and supplies an average volume of about $0{\cdot}5 \times 10^9$ m^3 per year (Celico, 1983). From the hydrogeological point of view, it can be defined as a basin-in-series aquifer system (sensu Celico *et al.*, 2006; Figure 2), due to fault zones that act as barriers to groundwater flow and compartmentalize the system (Celico, 1983). Thus, several important springs (mean

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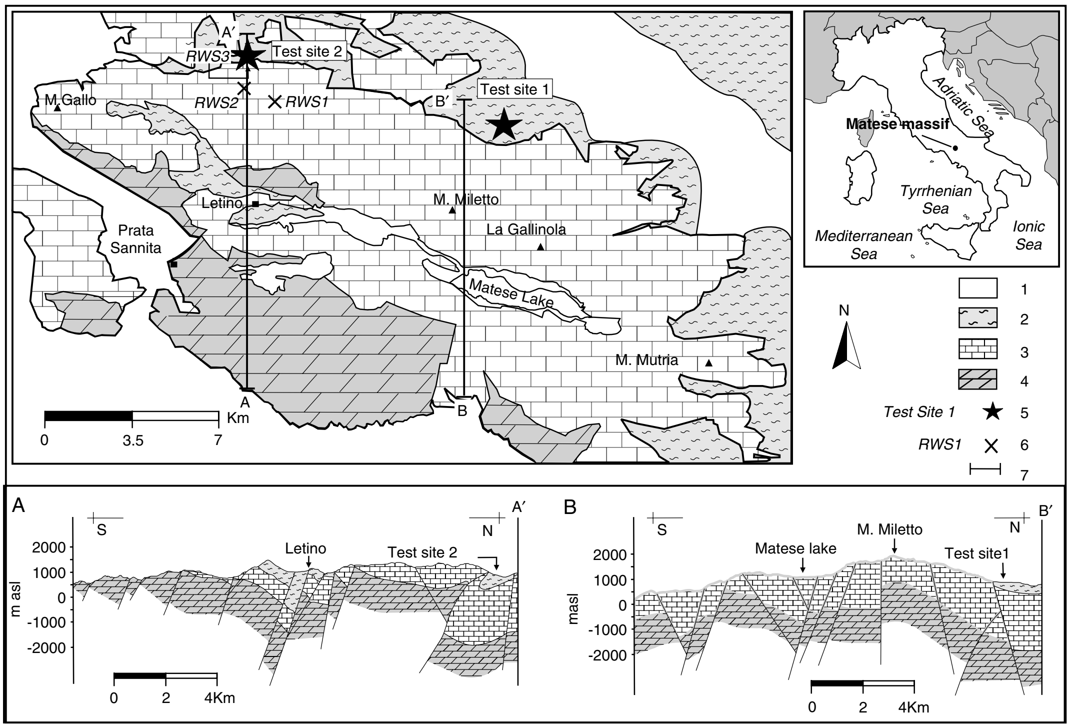

Figure 1. (A) Location of the study area; (B) Geologic profiles (after Robustini *et al.*, 2003, simplified) (1: Quaternary deposits; 2: siliciclastic and marly-clayey-calcareous successions; 3: limestone; 4: dolostone; 5: location of test sites; 6: rainwater sampler)

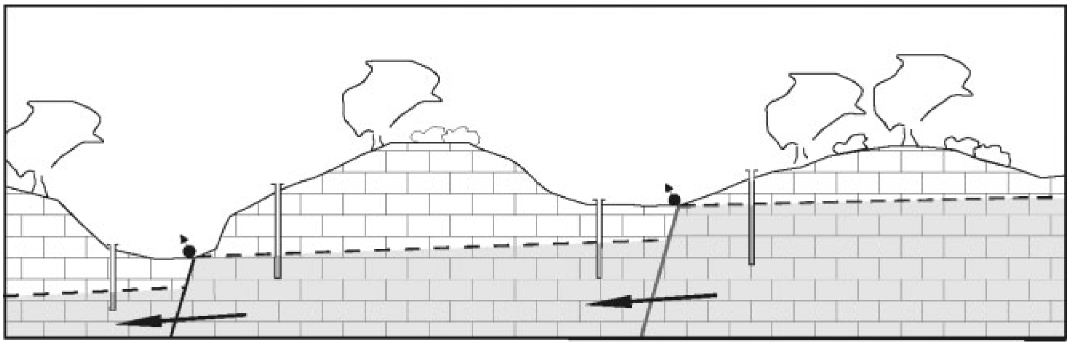

Figure 2. Schematic representation of a basins-in-series aquifer system (the arrows represent the groundwater flowthrough in fault zones; after Celico *et al.*, 2006)

annual discharge up to 4·7 m^3 s^{-1}) are fed by the hydrostructure. The northern side of the carbonate massif is bounded mainly by siliciclastic deposits and marly-clayey-calcareous successions (De Corso *et al.*, 1998; Di Bucci *et al.*, 2005). Two test sites were selected within these lower permeability deposits.

At test site 1, the data coming from 20 borehole stratigraphies show a sequence of foredeep siliciclastic deposits that consist of fine- to coarse-grained quartzose sandstone cemented with calcite. Gray and black marls, clayey marls, marly clays and clays are locally inter-bedded (Frosolone Formation; Tortonian-Messinian Miocene; Selli, 1957). The siliciclastic bedrock lies below a weathered horizon (2–8 m thick) made up of a surface soil with significant organic contribution and a lower mineral/rock grain debris chemically weathered.

At test site 2, the data coming from five borehole stratigraphies show carbonate slope and basin deposits that consist of laminated green marls and clayey marls, marly limestone, limestone, and clays (Macchiagodena, Longano and Frosolone Formations; Oligocene—Messinian; Pescatore, 1963). The spring SC [about 670 m above sea level (m asl)] is located within the marly-clayey-calcareous rocks, about 150 m north from the main reverse fault that marks the northern edge of the carbonate massif. The borehole stratigraphic data also suggest the existence of a second reverse fault within the marly-clayey-calcareous succession, close to the spring (Figure 3). The spring has a discharge ranging from 0·01 to 0·25 m^3 s^{-1} (annual mean ~0·10 m^3 s^{-1}).

MATERIALS AND METHODS

At test site 1, the hydraulic conductivity of siliciclastic rocks was calculated using the results coming from

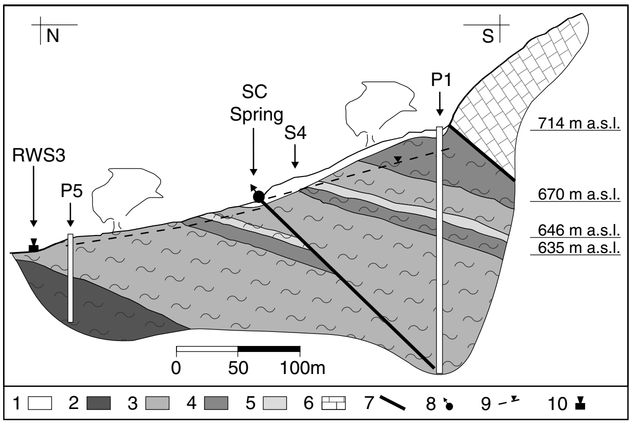

Figure 3. Hydrogeological profile at test site 2 (1: debris; 2: clayey deposits; 3: marly-clayey deposits; 4: clayey-marly deposits; 5: calcareous deposits; 6: carbonate massif; 7: reverse fault; 8: spring; 9: hydraulic head; 10: rainwater sampler)

124 Lugeon tests (Lugeon, 1933) that were carried out in 20 boreholes (Italsonda, 1995). The tests were conducted on confined borehole sections 5 m in length, with five pressure steps, making sure that the discharge injected was stabilized and measuring the undisturbed groundwater level before injection. It was ramped up over three increasing pressure steps in each test, then ramped back down two decreasing steps at pressures that matched the ramping up pressures.

At test site 2, rainwater samples for stable isotope (δ^{18}O) analyses were collected in three rain samplers RWS1, RWS2 and RWS3, along the northern slope of the carbonate aquifer, at 1150, 1014, and 635 m asl, respectively. The sampling was carried out on a monthly basis from November 2007 to October 2008. Polyethylene bottles (10 l) containing about 300 ml of vaseline oil to prevent evaporation processes even under very hot summer conditions were used to collect the samples. Oil contamination was carefully avoided while syringing the water samples out of the bottle. On February 2008 (high-flow period) and on June 2009 (low-flow period) water samples for stable isotope (δ^{18}O) analyses were collected (Figure 3) (1) at spring SC, (2) at well P1 (150 m deep and fully screened), drilled within the marly-clayey-calcareous rocks, upgradient of the spring, and (3) at well P5 (50 m deep and fully screened), drilled within the same succession, downgradient of the spring. Isotopic analyses were carried out at the Laboratorio di Geochimica Isotopica of the University of Parma and the Istituto di Geoscienze e Georisorse of the CNR, Pisa, Italy. The analytical precision was ±0·1‰. The composition of δ^{18}O is reported in δ‰versus Vienna Standard Mean Ocean Water (V-SMOW)standard. Taking into consideration the known altitude effect (Dansgaard, 1954), δ^{18}O was used as environmental tracer (Clark and Fritz, 1997; Kendall and McDonnell, 1998; Aggarwal *et al*., 2005) to identify the groundwater flow system discharging at spring SC.

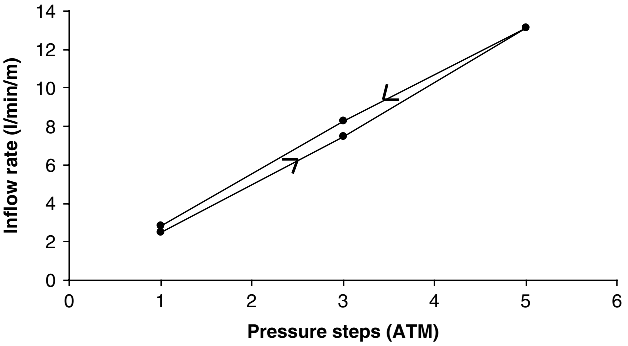

Figure 4. Example of graph of Lugeon test results at test site 1

RESULTS AND DISCUSSION

Test site 1

The hydraulic conductivity of siliciclastic deposits ranged from $1{\cdot}1 \times 10^{-8}$ to $2{\cdot}7 \times 10^{-6}$ m s^{-1} (an example of results of Lugeon test is shown in Figure 4), in good accordance with values obtained in other countries for the same rocks (Freeze and Cherry, 1979). At some boreholes the rock mass did not absorb the injected water in the deepest parts of the borehole. This threshold was 30 m depth (below ground surface) at two boreholes and was 35 m at another one. At a depth shallower than 15 m from the ground the hydraulic conductivity was usually higher than $5{\cdot}2 \times 10^{-7}$ m s^{-1} with a mean value of $1{\cdot}2 \times 10^{-6}$ m s^{-1}, a geometric mean of $1{\cdot}0 \times 10^{-6}$ m s^{-1}, and a median of $1{\cdot}3 \times 10^{-6}$ m s^{-1}. On the whole, the median values of hydraulic conductivity as well as the geometric means rapidly diminish with depth (Figure 5). The variation of median values can be described by the following empirical power law which is based on the best fit found by the authors:

$$K = 0{\cdot}0017\ d^{-2{\cdot}9358}$$

where, K is the hydraulic conductivity of siliciclastic rocks (in m s^{-1}) and d is the depth below ground surface (in m).

Comparing hydraulic conductivity values derived from confined borehole sections with predominant sandstones to those calculated in sections where sandstones are inter-bedded with marls and clayey marls, the following scenario is observed (Table I). For both lithologies, hydraulic conductivity rapidly diminishes with depth, clearly suggesting that this variation affects the whole sedimentary succession. Moreover, at a depth shallower than 15–25 m from the ground, hydraulic conductivity values do not show appreciable differences between lithologies. However, from this depth and deeper, the hydraulic conductivity of sandstones is up to one order of magnitude lower than that calculated where sandstones are inter-bedded with marls and clayey marls.

A general trend of permeability decrease with depth has also been reported for other fractured media in other areas. For example, it was found as one of the most characteristic features of fractured crystalline rocks (e.g. Davis and De Wiest, 1966) where permeability is

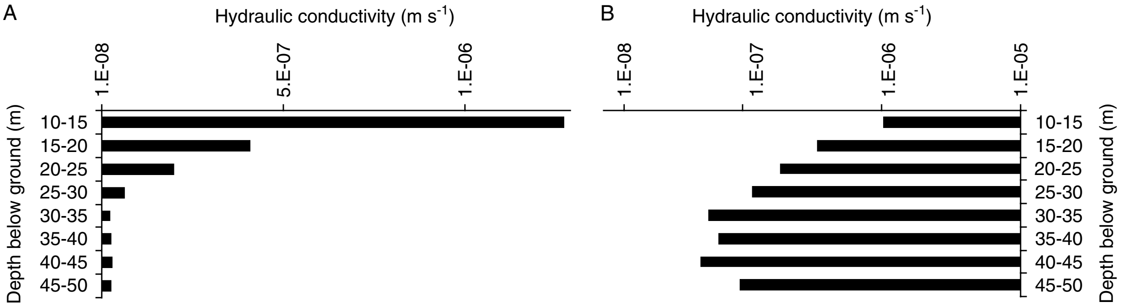

Figure 5. Variation of hydraulic conductivity with depth within the siliciclastic deposits at test site 1 [(A) median values; (B) geometric means]

Table I. Hydraulic conductivity (m s^{-1}) calculated in confined borehole sections with predominant sandstones (S) or sandstones inter-bedded with marls and clayey marls (SMC)

Depth below ground surface (m)	Mean	Mean	Geometric mean	Geometric mean	Median	Median
	S	SMC	S	SMC	S	SMC
10–15	1·5 10^{-6}	1·0 10^{-6}	1·4 10^{-6}	8·3 10^{-7}	1·9 10^{-6}	9·7 10^{-7}
15–20	6·2 10^{-7}	7·9 10^{-7}	3·1 10^{-7}	3·6 10^{-7}	3·2 10^{-7}	4·8 10^{-7}
20–25	9·4 10^{-8}	5·2 10^{-7}	9·9 10^{-8}	2·1 10^{-7}	6·3 10^{-8}	3·4 10^{-7}
25–30	5·7 10^{-8}	3·4 10^{-7}	5·0 10^{-8}	1·6 10^{-7}	3·8 10^{-8}	2·3 10^{-7}
30–35	1·1 10^{-8}	1·3 10^{-7}	3·1 10^{-8}	5·8 10^{-8}	1·1 10^{-8}	4·2 10^{-8}
35–40	2·6 10^{-8}	1·3 10^{-7}	4·1 10^{-8}	7·5 10^{-8}	1·1 10^{-8}	4·1 10^{-8}
40–45		9·6 10^{-8}		5·1 10^{-8}		2·8 10^{-8}

significantly lower at depths greater than about 100 m (Summers, 1972). In siliciclastic sequences, Runkel *et al.* (2006) observed a greater development of hydraulically active secondary porosity features, especially non-systematic fractures, close to the bedrock surface.

In the case study, taking into consideration the relatively limited thickness of the rock mass investigated, this trend with depth should be mainly due to stress release fracturing, a phenomenon that occurs because of unloading stress where rock has been removed. The effect of such a phenomenon may be an increase in permeability of the rock mass in the vicinity of the ground surface because of the increased density of joints and bedding plane partings (Ferguson, 1967; Sasowsky and White, 1994). Other processes, such as near-surface physical and chemical weathering may have affected this trend.

To summarize, at the study site different lithologies of the sedimentary succession show differences in terms of original permeability, but these differences do not seem to influence the effect of stress release fracturing and weathering on rock permeability in the uppermost bedrock.

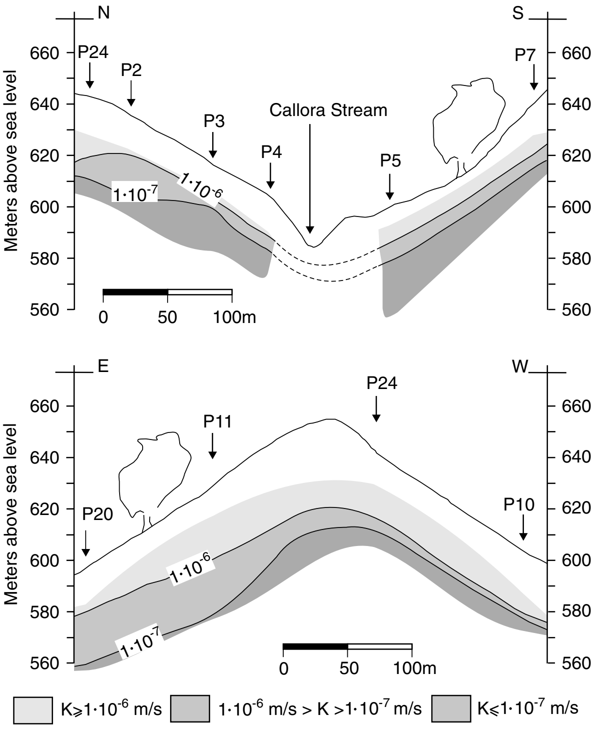

Figure 6. Variation of hydraulic conductivity with depth at test site 1

From the hydrogeologic point of view, permeability decrease with depth causes a layered distribution of the hydraulic conductivity of siliciclastic deposits at test site 1 (Figure 6) and then non-uniform hydrogeologic relationships between these deposits and the carbonate massif. Taking into consideration the hydraulic conductivity values ($6{\cdot}9 \times 10^{-7}$ to $3{\cdot}5 \times 10^{-6}$ m s^{-1}; Celico *et al.*, 2006; Petrella *et al.*, 2007) calculated through Lugeon tests for the carbonate protolith (the country rock where fault-related permeability structures are absent) within the Matese massif, the following scenario can be depicted:

- The upper 15 m of siliciclastic deposits are characterized by hydraulic conductivity values very close to those of carbonate rocks;

- Thus, from this depth and shallower, there is no significant contrast in permeability between the different rock types along the boundary;
- Such findings show that significant groundwater discharge is allowed from the massif towards the siliciclastic deposits if the hydraulic head in the massif is higher than a threshold depth, which was about 15 m below ground at this site;
- From this depth and deeper, the groundwater discharge abruptly diminishes to become negligible below 25–30 m below ground.

Test site 2

The results of isotopic analyses on rainwater samples were used to calculate the δ^{18}O vertical gradient at the study site (−0·16‰/100 m; Figure 7). This gradient is consistent with the overall mean value of the vertical δ^{18}O gradient calculated throughout Italy (fairly close to −0·20‰/100 m; Longinelli and Selmo, 2003) and the gradient found at another site in southern Italy by Paternoster *et al.* (2008) (−0·17‰/100 m). It is also in the range of values observed throughout the world (−0·15‰ to −0·50‰/100 m; Clark and Fritz, 1997). Such a gradient was then used to calculate the mean elevation of the recharge areas of spring and groundwater.

The δ^{18}O content in water collected at spring SC (−7·82‰ in high-flow period and −7·87‰ in low-flow) is very close to that of water collected at well P1 (−7·67‰ in high-flow period and −7·61‰ in low-flow period). For both the spring and well P1, seasonal variations were lower than the 2σ error of the δ^{18}O analyses. Conversely, these values are significantly more depleted than the value observed in the groundwater sample collected at well P5 in high-flow period (−7·27‰), downgradient of the spring. The difference between spring SC and well P1, and well P5 is lower in low-flow period. In such a period, the δ^{18}O content in water collected at well P5 is −7·54‰. Taking into consideration the local δ^{18}O vertical gradient, the isotopic content of spring water suggests a mean elevation of the recharge area ≅1300 m asl. Differently, for groundwater collected at well P5, it is 947 m asl in high-flow and 1115 m asl in low-flow period. These results depict the following scenario:

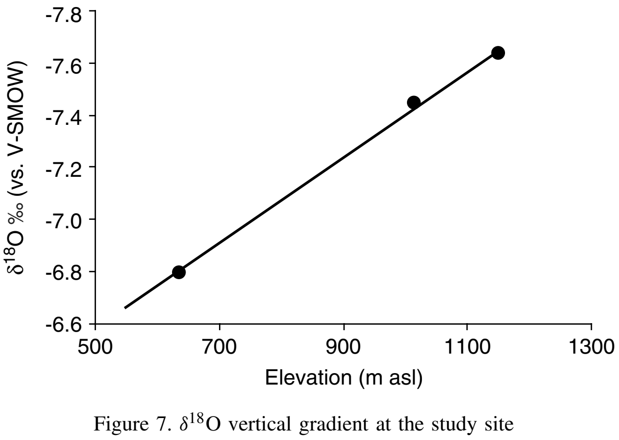

Figure 7. δ^{18}O vertical gradient at the study site

- The spring SC is clearly fed by the carbonate massif whose maximum elevation is about 1350 m asl, thereby suggesting that a significant groundwater discharge is allowed along the boundary between carbonate rocks and marly-clayey-calcareous deposits;
- Thus, the reverse fault that lies between carbonate and marly-clayey-calcareous deposits does not behave as an aquiclude or aquitard; instead, it appears to partially impede groundwater discharge, as Celico *et al.* (2006) reported for the normal faults investigated within the carbonate massif;
- The shallower and more densely fractured marly-clayey-calcareous sequence does not behave as aquitard and allows the groundwater to flow towards the spring SC;
- Because the spring is located along the reverse fault detected within the marly-clayey-calcareous sequence, the latter seems to behave as a permeability barrier; the barrier action may cause the hydraulic head to reach the ground surface upgradient;
- However, this reverse fault partially impedes groundwater flow because the isotopic content of groundwater collected at P5 is more depleted than the content (−6·80‰) of rainwater collected within the marly-clayey-calcareous succession; thus, a significant mixing occurs at this site between groundwater flowing from the carbonate massif and local infiltration water; as expected, in low-flow period, the contribution of local infiltration water is lower, as demonstrated by the more depleted δ^{18}O content in P5-water.

CONCLUSIONS

This study demonstrated that siliciclastic deposits and marly-clayey-calcareous successions in the Apennine chain (southern Italy) may allow significant groundwater discharge from carbonate aquifers. Thus, they do not everywhere behave as aquitard, contrary to the previous model (Celico, 1986). Instead, groundwater flows through the upper part of these successions, where stress release fracturing enhanced rock permeability in the near-surface bedrock. This vertical zoning and the very low hydraulic conductivity values calculated in the deeper siliciclastic bedrock at test site 1 suggest that this phenomenon is significant only where the hydraulic head in carbonate aquifers is high enough to reach the bottom of more densely fractured siliciclastic (or marly-clayey-calcareous) rocks. At test site 2, no Lugeon tests allowed to experimentally observe such a variation with depth. However, because strata are south-dipping, groundwater discharge from the carbonate aquifer cannot occur only through higher permeability calcareous layers (Figure 3), and groundwater discharge must involve the marly-clayey-calcareous sequence as a whole. The relatively high permeability of the shallower part of these sedimentary successions is confirmed by preliminary investigations at another site in southern Italy, where continuous groundwater head measurements in wells show fast response of groundwater to recharge events.

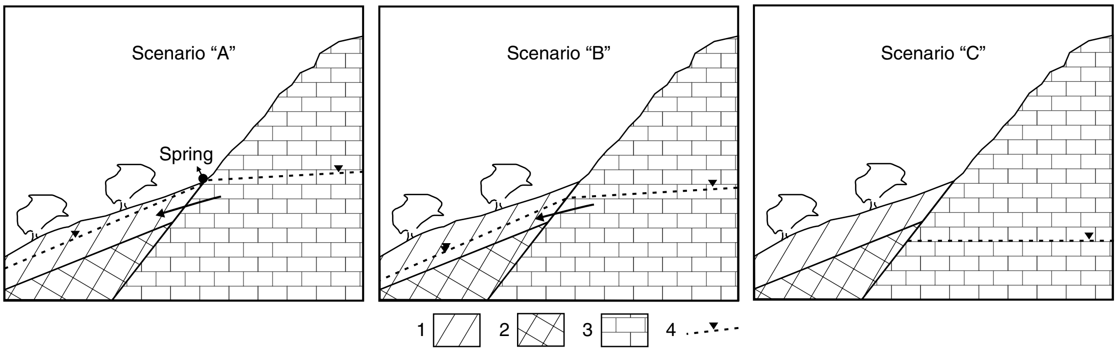

Figure 8. A possible model of interaction between carbonate aquifers and siliciclastic or marly-clayey-calcareous successions (1: decompressed siliciclastic or marly-clayey-calcareous deposits; 2: siliciclastic or marly-clayey-calcareous deposits; 3: carbonate massif; 4; hydraulic head)

In the wider context of the southern Apennine chain, three main scenarios can be depicted (Figure 8):

- In a first scenario (A in Figure 8) the hydraulic head in the carbonate aquifer is higher than the bottom of more densely fractured rocks, but a significant contrast in permeability is observed at the transition between them; in such a scenario, the groundwater flows in part at a spring and in part through the more densely fractured rocks; the same scenario can be observed where the thickness of the more densely fractured rock interval is not sufficient to accommodate all inflow;
- In a second scenario (B in Figure 8) the hydraulic head in the carbonate aquifer is higher than the bottom of more densely fractured rocks and there is no significant contrast in permeability along the transition between them; in such a scenario, complete groundwater inflow is allowed and springs have not developed along the border of the carbonate massif;
- In a third scenario (C in Figure 8) the hydraulic head in the carbonate aquifer is lower than the bottom of more densely fractured rocks; in such a scenario, no significant groundwater flow is allowed from carbonates towards siliciclastic or marly-clayey-calcareous rocks.

Significant groundwater discharge from carbonate aquifers is also expected where damage zones enhance fault zone permeability within siliciclastic and marly-clayey-calcareous successions (Chester and Logan, 1986; Andersson *et al.*, 1991; Goddard and Evans, 1995), but no experimental data have been acquired up to now to support such a hypothesis in the study area. With regard to the hydrogeologic behaviour of tectonic discontinuities, the present study showed that reverse faults within marly-clayey-calcareous successions may partially impede groundwater flow, probably due to a better developed fault core. The fault core is defined as the structural, lithologic, and morphologic portion of a fault zone where most of the displacement is accommodated (Caine *et al.*, 1996). Fault cores may include single slip surfaces (Caine *et al.*, 1991), highly indurated, cataclastic zones (Chester and Logan, 1986), brecciated and geochemically altered zones (Sibson, 1977), or unconsolidated clay-rich gouge zones (Anderson *et al.*, 1983). Both the structure and the composition of fault cores, combined with thickness variations, play an important role in controlling the fluid flow properties of fault zone cores (Caine *et al.*, 1996). Some authors (Chester and Logan, 1986; Antonellini and Aydin, 1994) suggest that mineral precipitation and/or grain-size reduction generally yields fault cores with lower porosity and permeability than the adjacent protolith.

To summarize, the research demonstrated that siliciclastic and marly-clayey-calcareous successions may locally be a groundwater source within the southern Apennine chain. They have hydraulic features analogous to those present in fractured carbonates and aquifer-like behaviour in the near-surface bedrock and perhaps even at greater depths. This potential for groundwater discharge in rock units traditionally treated as aquitards must be fully considered in the development of subsequent groundwater flow schemes and water balances in carbonate aquifers in southern Italy.

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