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Groundwater in Metamorphic Rocks with Systematic Fractures: Inhomogeneous Systems

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A b s t r a c t: The distribution of springs in a mountainous area of NE Portugal (the Padrela Mountain) with Silurian metamorphic rocks (quartzites, phyllites, carbonaceous slates) and Hercynian granites is interpreted as a function of: a) the fracture patterns with their specific bearings and spring densities (N_k); b) the planar porosities and conductivities of the different rock types, as approached with systematic measurements of the fracture densities (N) and openings (b) to determine the average Nb^3 of each rock type. A pumping test made on an exploration well was used to discriminate four regimens of transmissivities ranging between 10^{-4} and 7×10^{-4} m^2/s. The successive transmissivities are to be interpreted as showing: a) the prograde zones of water outflow (thrust zone, quartzites, quartzites with phyllites and quartzites); b) the stepwards functioning of fracture systems with lower and lower conductivities.

Introduction

The fracture pattern in massifs made of homogeneous and isotropic rocks (e.g., granites) is essentially conditioned by the orientation of the tectonic stress field. In inhomogeneous rocks (e.g., quartzites, phyllites), the nature and attitude of the anisotropies complement the influence of the stress field, and this double influence produces a systematic pattern of fractures.

The groundwater movement in crystalline rocks is controlled by the planar hydraulic conductivities, which are a function of the fractures density and opening. As a direct consequence of anisotropy, the hydraulic conductivity in these rocks, as measured from some representative sample, will not be equal in all directions, and this should be particularly clear in metamorphic rocks because of their characteristic systematic fractures. The lithological diversity may also control the hydraulic behavior of metamorphic rocks; in principle, these rocks may be regarded as systems of multiple transmissivities, each one

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representing a volume of rock within which the hydraulic properties are conservative.

In this paper, both the drawdown of the potentiometric surface and the distribution of perennial springs found on a 25 km^2 area of a mountainous region of Northern Portugal (the Padrela Mountain) were checked against the rock types and their fracture patterns.

Geological setting

The studied area comprehends the sector of the Padrela Mountain between Tinhela de Baixo and Lagoa (Vila Pouca de Aguiar, Northern Portugal). Its a square with 25 km^2 area limited by the M and P Gauss coordinates: 245,505 and 250,510 km.

The Balugas area (small village in the center of the studied area) is situated on the Galiza Média Trás-os-Montes tectonic zone, which is a domain of the Centro Iberian zone. The regional geology (Fig. 1) is essentially characterized by Hercynian granites which have intruded NW-SE trending Paleozoic quartz rich phyllites, carbonaceous phyllites and quartzites. These metamorphic units may be interpreted either as Lower and Intermediate Peritransmontano (Portugal Ferreira 1965) or as Basal and Lower Peritransmontano (Noronha & Ribeiro 1993).

In the 25 km^2 that have been studied, one may define a geological structure of piled tectonic laminae separated by thrusts (Fig. 2). The three mapped laminae were characterized by Portugal Ferreira & Pacheco (1993):

Laminae A, from the bottom to the top: 1) quartzites, 2) fine grained banded phyllites with interlayered graphitic slates, 3) carbonaceous phyllites, 4) quartzites, 5) a complex with graywaques, reddish phyllites and quartzites;

Laminae A': 1) unit 5 of *A*, 2) quartzites, 3) quartz rich banded phyllites, 4) quartzites;

Laminae A'': units 2-4 of *A'*.

Pelitic hornfelses occur around the granites. Cover deposits comprehend alluvial and colluvial sediments.

Springs and their relationship with fractures and lithologies

Most of the springs in the study area are spatially connected and hydraulic dependent from discrete mapped fractures (Figs 3 and 4). These fractures may be classified on the basis of:

a) The orientation groups, which are coherent with the major Hercynian fold axes (F_1 and F_2) and therefore are discriminated as longitudinal L_1 (N40±10°W) and L_2 (N60±10°W), cross C_1 (N50°E) and C_2 (N30°E), diagonal

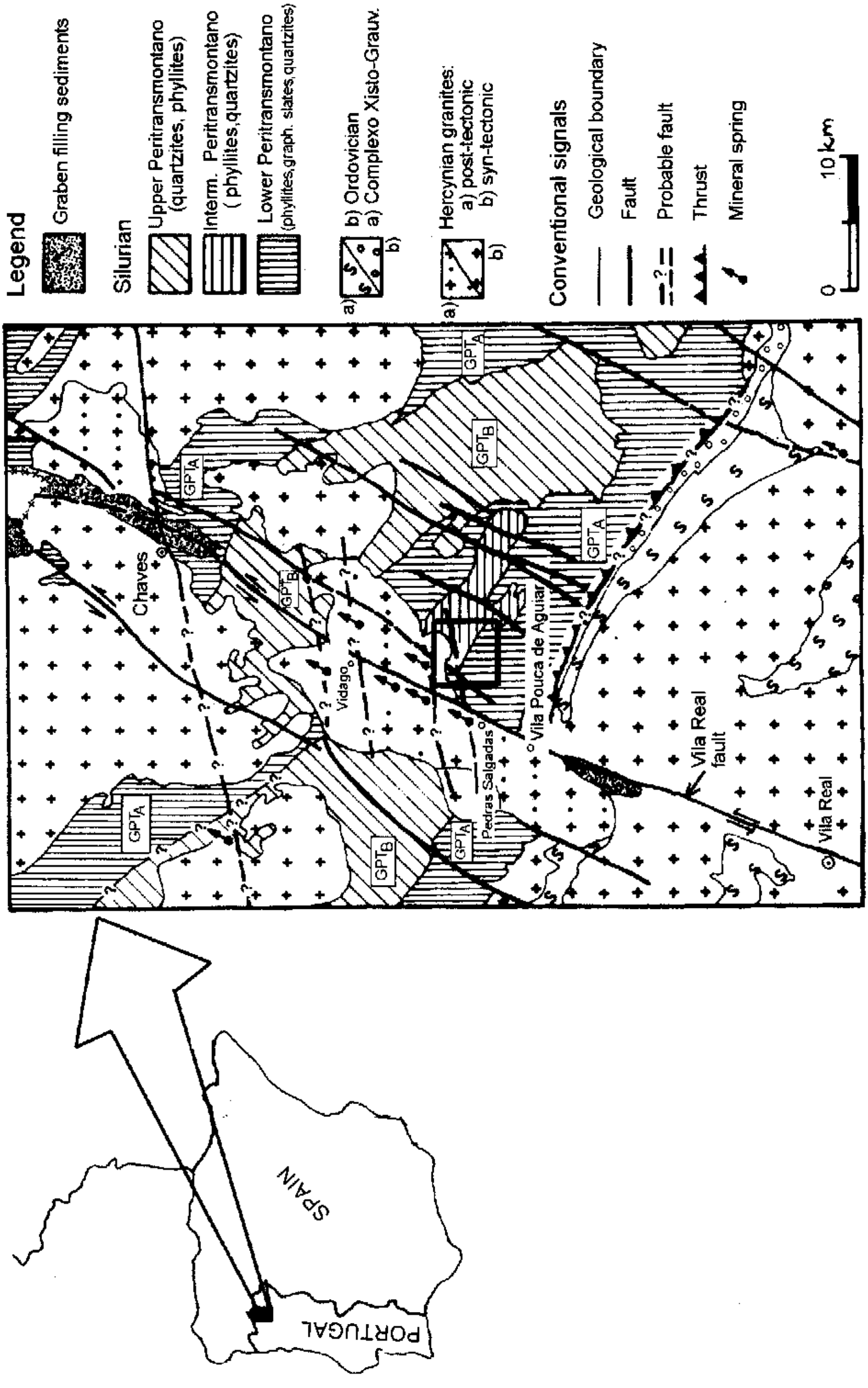
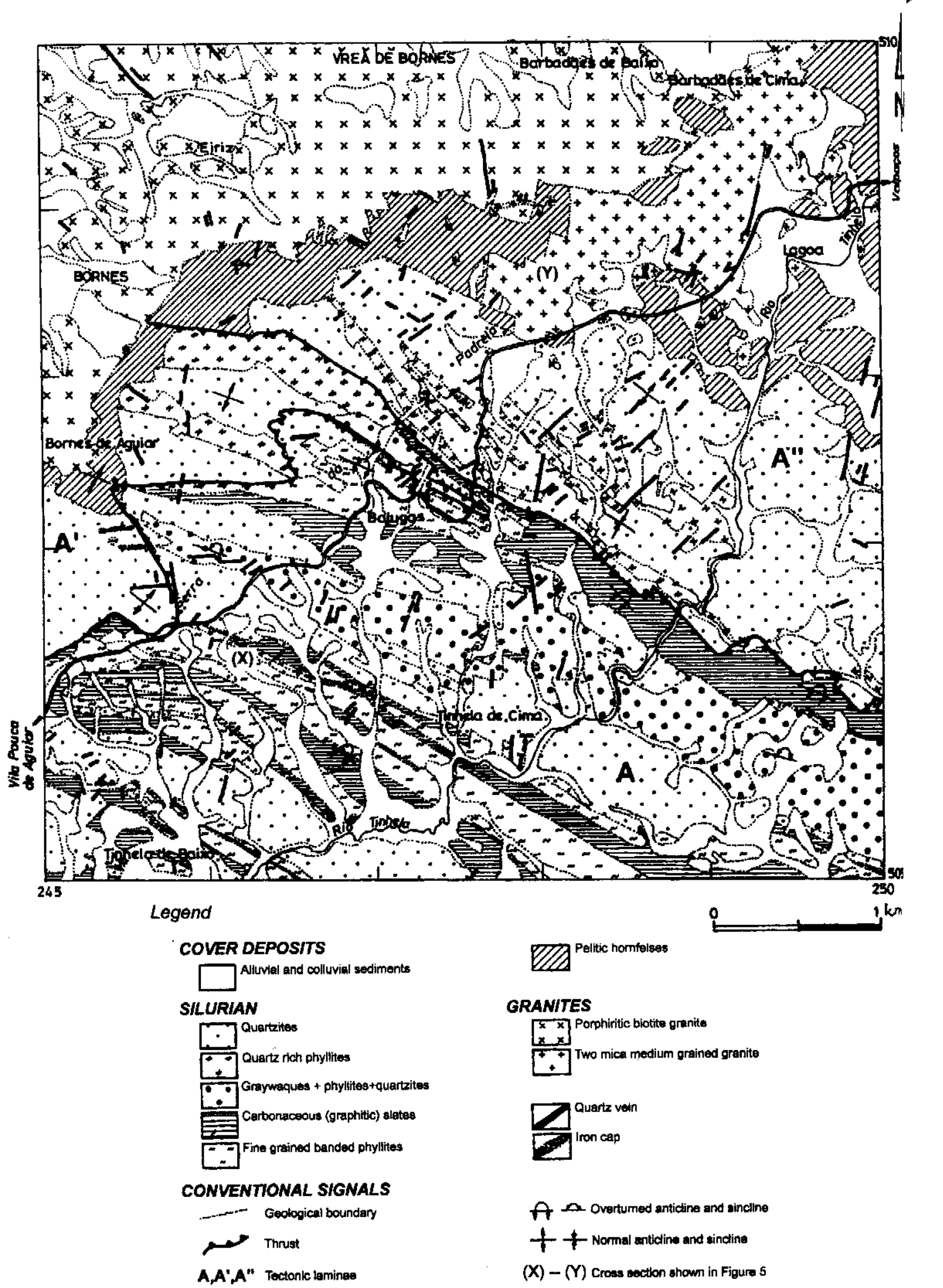


Fig. 1. Geological framework of the region indicating the position of the studied area


VREA DE BORNES
Barbadães de Baixo
Barbadães de Cima
Eiriz
BORNES
Bornes de Aguiar
Lagoa
(Y)
(X)
A'
A''
A
Balugas
Tinhela de Cima
Tinhela de Baixo
Rio Tinhela
Vila Pouca de Aguiar
510
245
250
Legend
0
1 km
COVER DEPOSITS
Alluvial and colluvial sediments
SILURIAN
Quartzites
Quartz rich phyllites
Graywaques + phyllites+quartzites
Carbonaceous (graphitic) slates
Fine grained banded phyllites
Pelitic hornfelses
GRANITES
Porphiritic biotite granite
Two mica medium grained granite
Quartz vein
Iron cap
CONVENTIONAL SIGNALS
Geological boundary
Thrust
A,A',A'' Tectonic laminae
Overturned anticline and sincline
Normal anticline and sincline
(X) – (Y) Cross section shown in Figure 5

D_1 (N20°E) and D_{1a} (N80°E) and D_2 (NS) and D_{2a} (N60°E). The Alpine faulting tends to play along these azimuths, mostly following the systems C_2 and D_2, and is also represented by the system N10°W;

b) The frequency (N) of fractures, herein represented by the total lengths;

c) The frequency (N_k) of springs, which is expressed by the number of springs per kilometer of lineament;

d) The fracture openings (b), which are very relevant for the planar hydraulic conductivities. As the major axis of the active external stress field should be oriented NW-SE (Cabral 1996), the L_1 and L_2 fractures and joints are expected to be more opened. This is difficult to confirm as L joints and foliations are hardly distinguishable. Nevertheless, in a quartzitic outcrop as well as in a liditic outcrop near a thrust zone, L joints were found to have from 1 to 4 cm openings.

Considering criteria (a) and (c), and taking into account the Summer outflows of the mapped springs, it is possible to evaluate the extent to which the fracture systems control the distribution of springs and the natural groundwater discharge in the area (Tab. 1a). It is very striking the differences found for the affiliation of springs on the fracture systems, while using overlapped maps (fourth column, a) and field work data (b). Based on the results of this last methodology, it becomes apparent that the longitudinal and Alpine orientations are important in regard to groundwater movement. It has to be mentioned that the discharge is under evaluated because there are springs exploited for personal use whose discharge rates could not be measured, and the base flow of the Tinhela river is not monitored.

The distribution of springs and the natural groundwater discharge are also conditioned by lithology. The density (number of springs per square kilometer of outcrop) and the Summer yields of perennial springs are depicted in Table 1b for each lithostratigraphical unit. The quartzites are responsible for two thirds of the natural outflow in the area.

Conclusions

Some pumping tests were made on an observation well that had been drilled down to 110 meters and only became productive where it crossed the thrust zone of the contact between the phyllites and the underlying so confined quartzites (Fig. 5).

The semi-logarithmic plot of the drawdown data versus time shows a picture of a leaky aquifer with an "overall" transmissivity of 5.5×10^{-4} m²/s. The interpretation of the data registered during some short-duration pumping tests,

Fig. 2. Geological map showing lithological diversity and structure

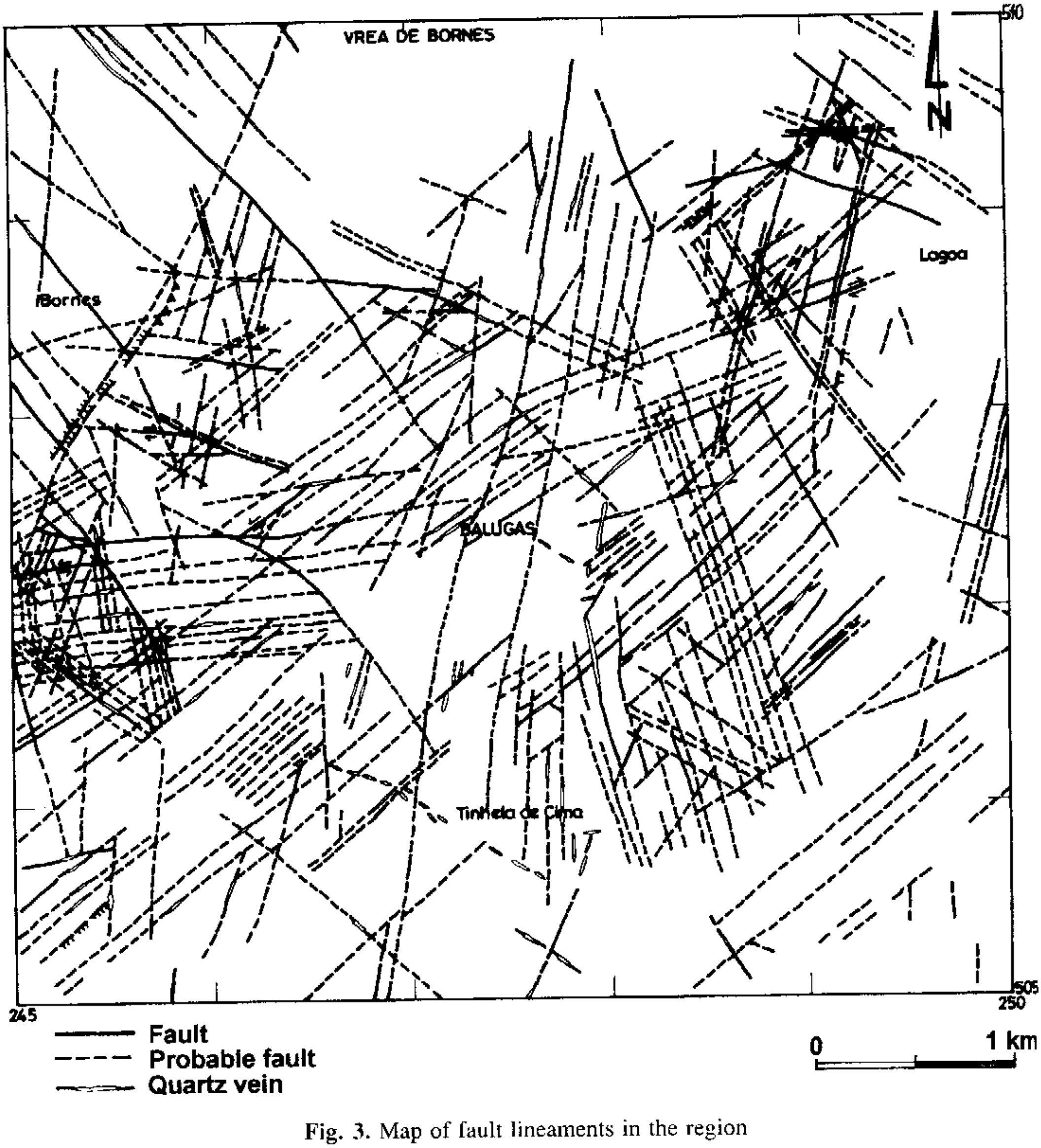


Fig. 3. Map of fault lineaments in the region

with different discharge rates, and a 10-days pumping test, at 3 l/s (Figs 6a and 6b, Tab. 2), might be used to discriminate a system of multiple transmissivities which appears to be geologically acceptable. These transmissivities (m^2/s) are ordered on the sequence: $T_1 = 7.0\times10^{-4}$, $T_2 = 2.0\times10^{-4}$, $T_3 = 10^{-4}$, $T_4 = 2.6\times10^{-4}$.

By considering the volumes of extracted water (and the corresponding rock volumes) and geological data, it may be proposed that transmissivities T_1-T_4 are explained by the rock heterogeneities; they correspond to the progressive

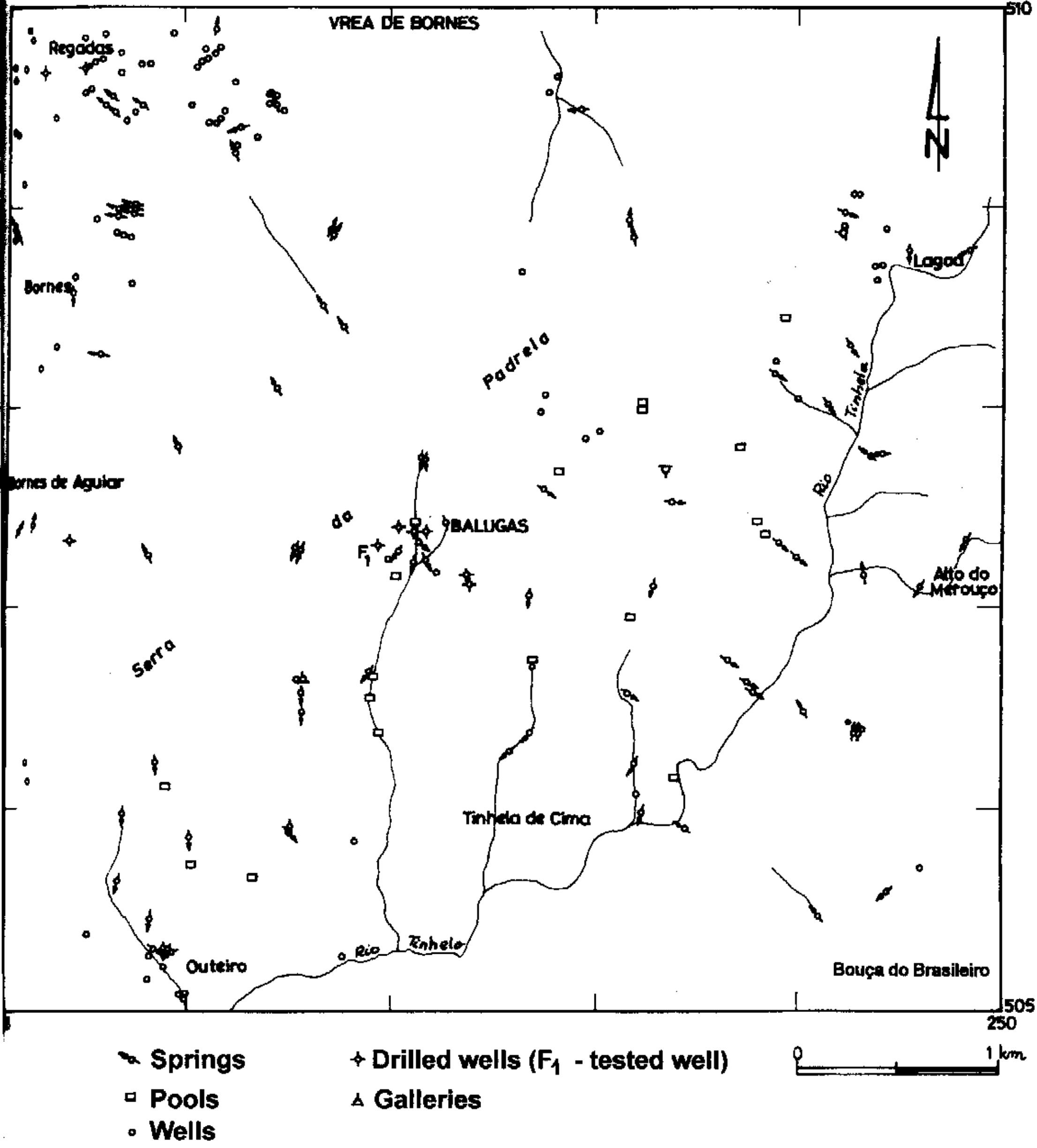


Fig. 4. Map with springs, pools, wells and drilled wells in the region

integration of the following rock volumes (cf. Fig. 5): R_1 — thrust zone; R_2 — expansion to the quartzites (Q_1) but with the drawdown influenced by the above lying barrier of phyllites (X_B); R_3 — further expansion to the quartzites with interlayered phyllites (Q_3 plus F_{qb} plus Q_4); and R_4 — comprehending the

Table 1a. Relation between the orientation of fracture systems and the distribution and Summer outflows of springs; N.A. — not attributed to a system; assumed classes of outflow: Eph — ephemeral; VL — very low (average discharge around 0.05 l/s); L — low (0.1 l/s); M — medium (0.2 l/s); H — high (0.6 l/s)

System	Orientation	Total extension [km]	Number of springs		Springs per km of lineament (N_k)		Springs per class of outflow					Measured Summer discharge [l/s]
			(a)	(b)	(a)	(b)	Eph	VL	L	M	H	
$L_1 + L_2$	N30-70°W	34.4	12	30	0.35	0.87	9	5	6	5	5	4.85
C_1	N50°E	66.9	22	0	0.33	0.00	0	0	0	0	0	0.00
$C_2 + D_1 + D_2$ (c)	NS-N30°E	51.2	5	22	0.1	0.43	3	4	6	6	3	3.80
$D_{1a} + D_{2a}$	N60-80°E	28.8	5	2	0.17	0.07	0	0	1	0	1	0.70
Alpine	N10W	?	?	9	?	?	1	4	2	2	0	0.80
N.A.	—	—	20	4	—	—	4	0	0	0	0	0.00
Total	—	—	64	67	—	—	17	13	15	13	9	10.15

(a) — results obtained by overlapping Figs 3 and 4 (Pacheco & Portugal Ferreira 1995); (b) results obtained using filed work data and hydrogeological criteria; (c) — also Alpine azimuths.

Table 1b. Density of perennial springs and Summer yields in each lithostratigraphical unit (cf. units in Fig. 2)

Unit	N	A [km^2]	d	Perennial springs per class of outflow				Q [l/s]
				VL	L	M	H	
$Q_1 + Q_2$	8	2.8	2.9	2	2	2	2	1.90
X_B	5	2.2	2.3	2	1	2	0	0.60
X_N	3	2.7	1.1	1	2	0	0	0.25
X_L	4	1.9	2.1	1	0	3	0	0.65
f_{qb}	2	1.1	1.8	1	1	0	0	0.15
$Q_3 + Q_4$	19	5.7	3.3	5	6	2	6	4.85
Hornfelses	6	2.3	2.6	0	2	3	1	1.40
Two mica granite	3	1.7	1.8	1	1	1	0	0.35
Total	50	20.4	2.5	13	15	13	9	10.15

Symbols: N, A, d, Q — number of springs, outcrop area, density of springs ($d = N/A$) and measured discharge rate in each unit, respectively; additional information identical to Tab. 1a.

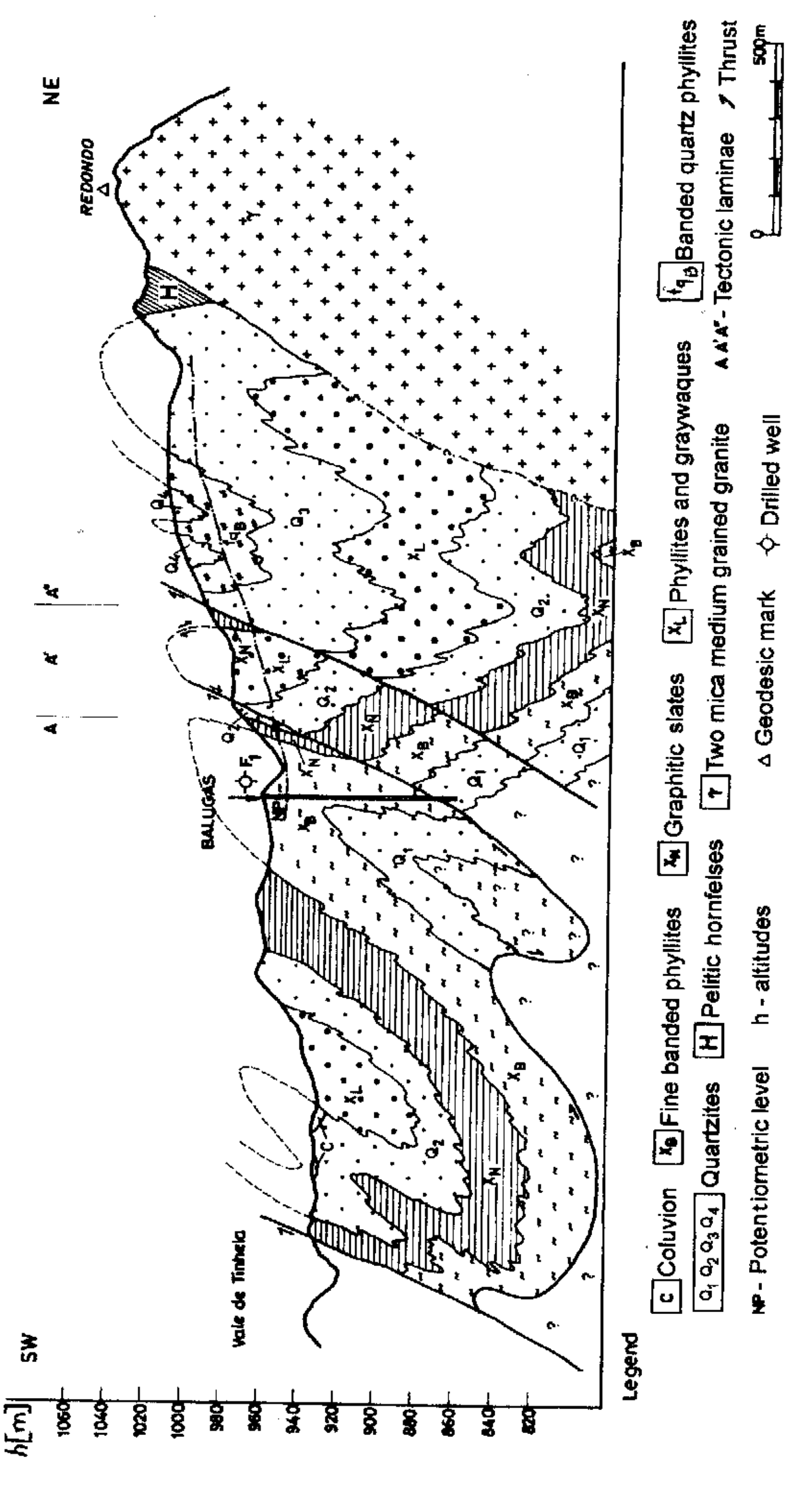


Fig. 5. Geological cross section to show the drilled well and structure

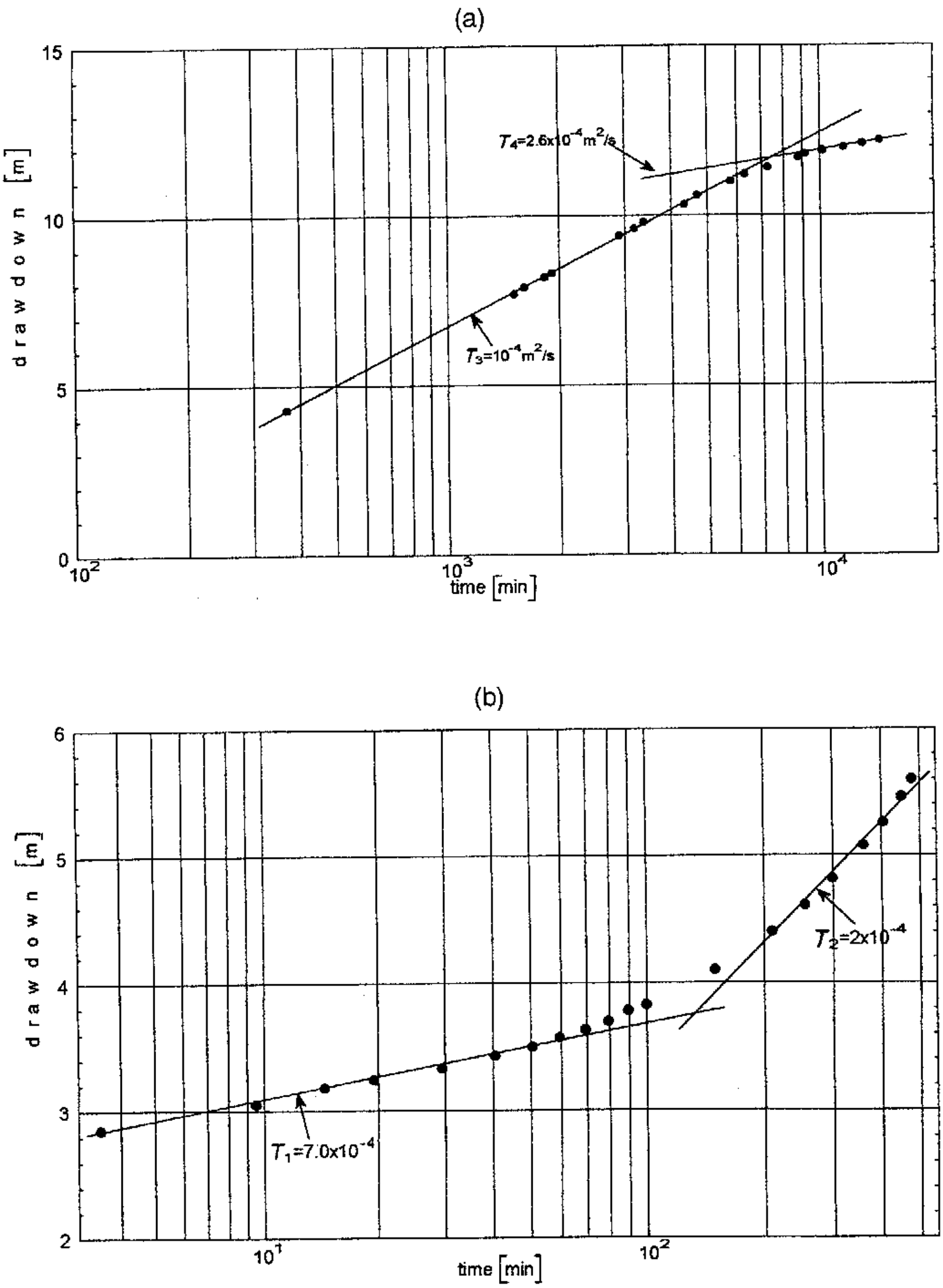


Fig. 6. Drawdown-time curves: a) short-term pumping test, b) 10-days test

Table 2. Results obtained with 7 short-duration pumping tests executed on the drilled well

Test	Q [l/s]	t [min]	Δs [m]	T_1 [m^2/s]	T_2 [m^2/s]
1	0.42	35	0	1.5×10^{-3}	—
2	0.57	45	0	1.5×10^{-3}	—
3	1.22	90	-0.18	5×10^{-4}	—
4	1.76	45	0.13	1.5×10^{-4}	—
5	1.84	45	0.16	1.0×10^{-4}	—
6	2.22	540	1.47	3.0×10^{-3}	2.7×10^{-4}
7	3.00	480	1.45	7.0×10^{-4}	2.0×10^{-4}

Symbols: Q — discharge rate; t — duration of the test; Δs — residual drawdown after t minutes of recovery; T — transmissivity.

quartzites which exist Northeastwards (Q_3). It is suggested that the groundwater mostly flows from the Northern compartment, and that the points of the drawdown-time curves where the gradients change are interpreted as having the geological significance of boundaries between rock units.

It was found that the fracture densities (N), openings (b) and "hydraulic influences" (Nb^3/m^2) measured on the rock domains R_1, R_3 and R_4, as seen on surface outcrops, as well as the distribution of springs (Tab. 1a and 1b), do not contradict this interpretation (Tab. 3). In order to envisage the pattern which may control the pumping test, the chosen outcrops are situated exactly on the

Table 3. Fracture densities (N), openings (b) and "hydraulic influences" (Nb^3/m^2) determined for rock domains R_1, R_3 and R_4, on the basis of 170 fractures and 1470 m² of outcrop area

Rock domain	Density N [number of fractures/m^2] (*)		Openings b [mm]		"Hydraulic influence" [Nb^3/m^2] (****)
	total	effective (***)	average	range	
R_1 (thrust zone) (**)	0.2	0.14	2.6	0-8	1.1
R_2	?	?	?	?	?
R_3 (on quartz phyllites)	0.1	0.03	1.6	0-9	0.3
R_4 (on quartzites)	0.2	0.13	2.7	0-13	4.2

(*) The density is under evaluated as the figures were calculated considering that a total scanning of the outcrops was made. This is only possible for absolutely clean outcrops.

(**) Only discrete fractures were measured (most of the zone is highly brechiated); observations were made extending 40 m Northeastwards from the thrust surface.

(***) Only the fractures with visible opening were considered.

(****) The Nb^3 was computed for each class of openings; $b/2$ was chosen as the b's were registered for its maxima along the visible length of the discrete fractures.

center of the studied area. The data used to define the hydraulic influences should be obtained after a careful analysis of sizable domains that ought to be representative of the different lithologies and their pattern of fractures. Notice that the contents of Tab. 3 are to be critically considered as the scanning of the fractures reported there covered only 170 fractures and 1470 m^2 of outcrop area. Due to the fact that there is a good correlation between the frequency of springs (N_k) and the frequency of fractures, it may be suggested that the hydraulic hierarchization of the fracture systems could be considered as a second source for the interpretation. For example, for the segment of the drawdown-time curve that shows a steady decrease of transmissivities (the one that includes T_2 (2.0×10^{-4} m^2/s) and T_3 (10^{-4} m^2/s)), the following interpretation could be chosen: the water stored in progressively less conductive fractures provides the necessary volume of groundwater for the pumping test. This applies for systematically different conditions of planar porosities. In general, for the rock massifs with pervasive anisotropic metamorphic rocks, such as foliated quartzites, foliated hornfelses, granulites, gneisses, amphibolites, quartz micaschists, where systematic fracture patterns are to be expected, each system of fractures should be studied for its particular conductivity and storativity.

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