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LARGE SELF-POTENTIAL ANOMALIES IN THE NOIR RI BASIN (ARDENNES, BELGIUM)

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SUMMARY. Self-potential anomalies of a total amplitude of 1100 mV were measured on the Plateau des Tailles (Ardennes, Belgium). The main anomalies, of negative sign, could be caused by electrochemical reactions in presence of a rock with electronic conductivity, in this case apparently a formation of black shales with graphite traces and pyrite mineralisations. Soil drainage class, as assessed through simple augering, turns out to be a main factor governing the extension of these anomalies. Besides this passive role played by hydrological factors, some positive anomalies could be associated with streaming potentials, betraying groundwater seepage from an aquifer, confined beneath a low-permeability soil or soil horizon. The conditions required for both mechanisms are reviewed and a simple structural interpretation is drawn.

Sterke spontane-polarisatieanomalieën in het bekken van de Noir Ri (Ardennen).
SAMENVATTING. Bij een resistiviteitsprospektie op het Plateau des Tailles (Ardennen) werden sterke spontane-polarisatie (S.P.) anomalieën (1100 mV) gemeten in het bekken van de Noir Ri. De grootste anomalieën, van negatief teken, worden waarschijnlijk veroorzaakt door elektrochemische reakties in aanwezigheid van een gesteente met elektronische geleidbaarheid, hier blijkbaar zwarte schiefers met grafietsporen en pyrietmineralisaties. De drainageklasse van de bodems heeft een doorslaggevende invloed op het verspreidingspatroon van deze grote negatieve anomalieën. Naast deze passieve invloed van hydrologische faktoren treden in dit gebied blijkbaar ook aktieve elektrofiltratieverschijnselen op, gebonden aan het doorsijpelen van grondwater van onder een weinig doorlaatbare bodem of bodemhorizont. Deze verschijnselen komen tot uiting in twee duidelijke positieve potentiaalanomalieën. De ontstaansvoorwaarden voor beide S.P. mechanismen in het bekken van de Noir Ri worden onderzocht en er wordt een eenvoudige strukturele interpretatie geschetst.

De fortes anomalies de potentiel spontané dans le bassin du Noir Ri (Ardennes).
RÉSUMÉ. Lors d'une campagne de prospection électrique sur le Plateau des Tailles, de fortes anomalies de potentiel spontané (1100 mV) furent mesurées dans le bassin du Noir Ri. Deux phénomènes distincts semblent être à leur origine. Les grandes anomalies négatives seraient dues à des réactions électrochimiques en présence d'une roche à conductivité du type électronique, apparemment des schistes noirs à traces de graphite et fortement minéralisés en pyrite. L'état de drainage du sol semble jouer un rôle prépondérant dans la répartition de ces anomalies négatives. En plus de ce rôle passif d'éléments hydrologiques, certaines zones à anomalies positives seraient le siège de phénomènes actifs d'électrofiltration, trahissant le suintement d'une nappe captive de sous un sol ou horizon pédologique à faible perméabilité. Les conditions requises pour la génération de ces deux phénomènes sont examinées et une simple interprétation structurale est esquissée.

Introduction

In autumn 1965 and 1966, a geoelectrical survey was carried out by the Laboratory of Geology of the University of Ghent on the Plateau des Tailles, a 600 meter high plateau in the Ardennes, Belgium (HENRIET, 1966).

Some fifteen electrical resistivity soundings (Wenner configuration) were located in the upper basin of the Noir Ri-Martin Moulin river. This small tributary of the Eastern Ourthe river, itself a Meuse affluent, has eroded a semicircular basin in the southern flank of the Baraque Fraiture monadnock (652 m). This basin is partially closed to the south by the ridge of Tailles (fig. 1).

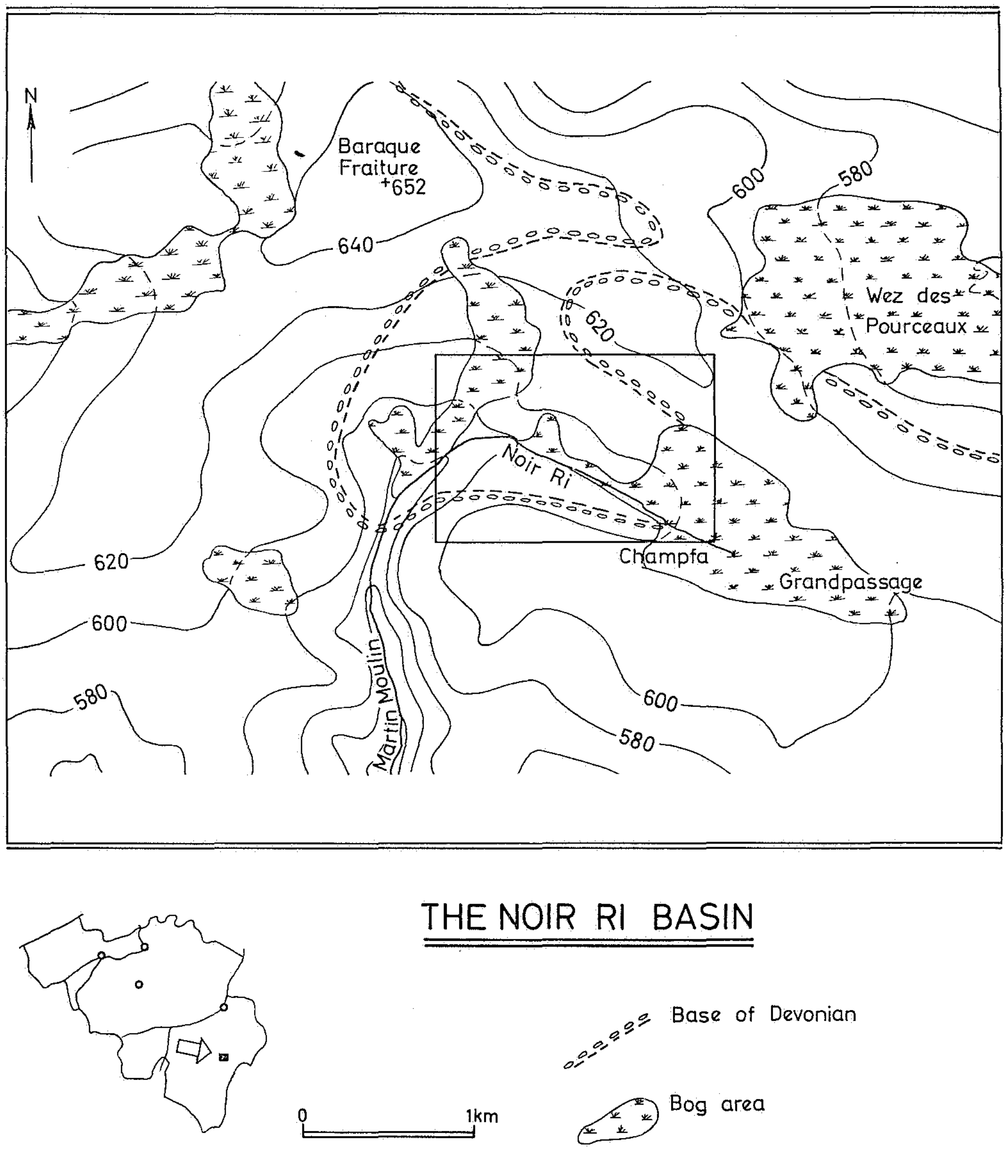

Fig. 1. Physiography of the Noir Ri basin.

The bedrock of the central part of the Noir Ri basin is mainly composed of folded and faulted Salmian (Tremadoc) shales, although the presence of still older rocks (e.g. Revinian, Upper Cambrian) could not be excluded. The ridges surrounding the basin are built up of sandstones, quartzites and conglomerates of lower Upper Gedinnian (Samrée sandstone, Waismes « arkose », basal conglomerate with coarse elements).

The geoelectrical survey revealed an extended high-conductivity zone in the bedrock of the central part of the basin. One of the soundings (557/33, fig. 2) showed a fast decrease of resistivity leading to final resistivity values close to zero. This feature was the first indication of the presence of a mineralisation with electronic conductivity in the bedrock of the Noir Ri basin.

In a later phase of the survey, a shallow exploration well was drilled by the Geological Survey of Belgium on the site of this electrical sounding. The top of the bedrock consisted mainly of darkgreen sandy shales. At a depth of 14 meter, the well penetrated a formation of black shales with quartz and pyrite mineralisations. X-ray analysis showed traces of graphite (J.P. CNUDDE, personal communication).

The presence of graphite traces, together with, although to a lesser extent, pyrite mineralisations, could explain the high-conductivity zone in the bedrock of the Noir Ri basin. Moreover, such mineralisations could be suspected to yield self-potential (S.P.) anomalies. This assumption led to the S.P. survey, reported in this paper.

Field technique and map compilation

A first S.P. profile crossed two potential troughs of several hundreds of mV (fig. 3, profile AE). Consequently, a network of measurements was spread over the bottom of the basin (fig. 4). Potential differences in each profile were measured in a cumulative way, one of the non-polarisable electrodes (copper-copper sulfate in porous pots) being kept on a base point, while the other one was gradually moved along a line. A new base point was chosen when the cable length (400 m) was exhausted. Equidistances between two consecutive measuring stations amounted to ten meters.

The bulk of measurements was compiled into a S.P. map (fig. 5). Zero potential level, always determined in an arbitrary way in a S.P. survey, was chosen here so as to match in a satisfying way with several potential flats observed on the profiles. The error on the zero level can amount to 50 mV, a value representing less than 10 % of the main anomalies.

Principle of interpretation

The S.P. map shows three main negative anomalies, which for convenience will be labeled the north-west (NW), the north-east (NE) and the south (S) anomaly. Moreover, a small potential high shows up between the NW and NE anomalies, whereas a broad positive anomaly (up to + 150 mV) stretches over the south-eastern angle of the bottom of the basin. These positive anomalies will be referred to respectively as the north (N) and south-east (SE) anomaly.

There is no absolute rule allowing to associate the polarity of an anomaly with a particular origin. However, it is generally admitted that electrochemical reactions in presence of sulfide ore bodies or graphitic rocks produce main negative anomalies, sometimes associated with minor positive centers, when the dipole (polarized ore body or graphitic shale formation) is not strictly vertical.

A second mechanism which could generate self-potential anomalies in nature is the circulation of water in porous rocks. Such electrokinetic phenomena, known as streaming potentials (QUINCKE 1859, 1860), lead to positive or negative S.P. anomalies, depending on the direction of flow. As a rule, potential highs are observed over rising flows, potential throughs over percolation zones.

As anomalies of some tens of mV are already considered as significant in mining geophysics, it is normal that the Noir Ri

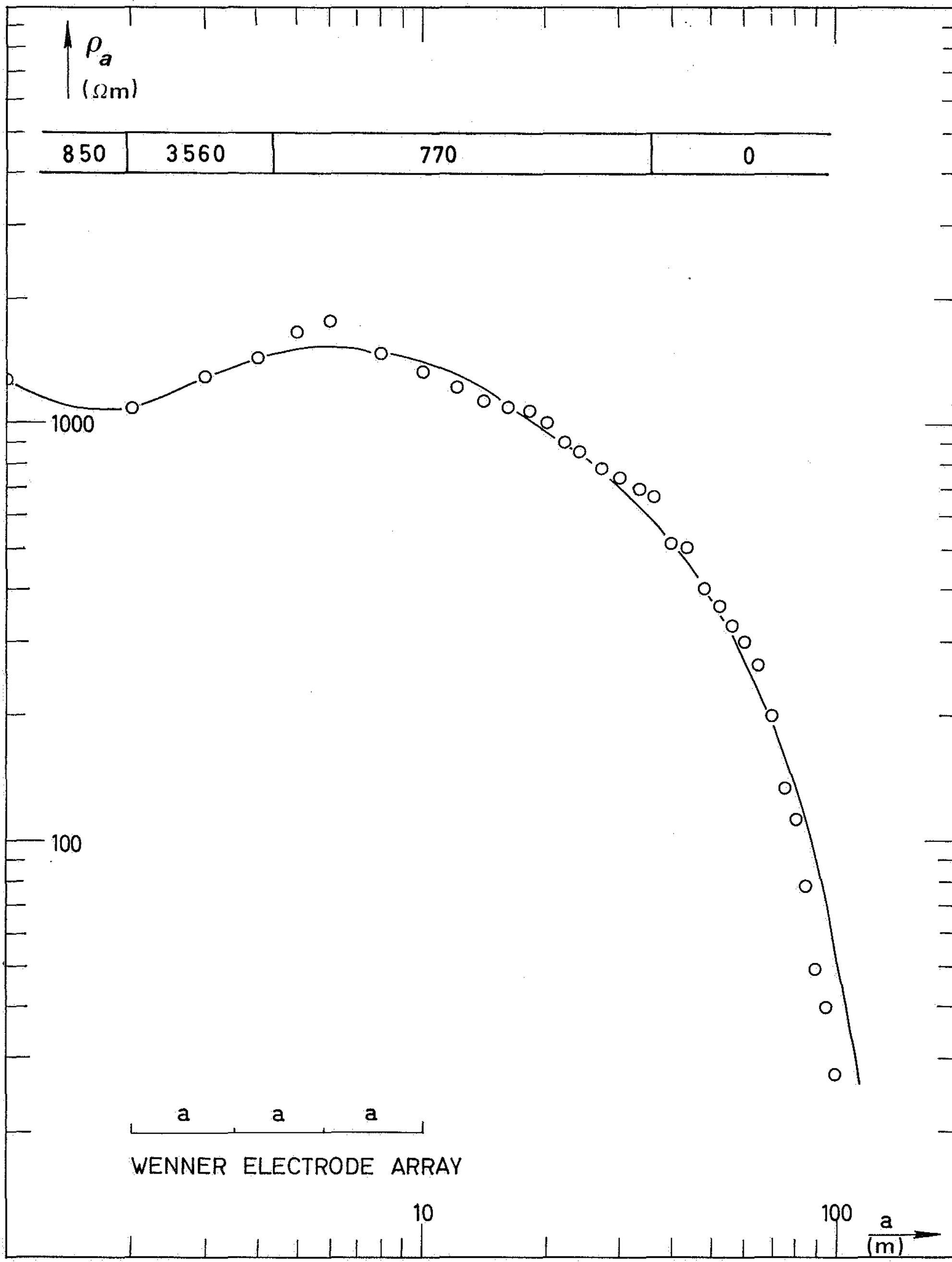

Fig. 2. Resistivity sounding revealing a high-conductivity formation at depth. The model curve (solid line) fitting the experimental points has been computed for the horizontally layered model shown in the upper part of the figure. Numerical values represent true resistivities, the depth of the contacts can be read from the horizontal log scale. The first layer (not shown on the model) has a resistivity of about 4000 Ωm and a thickness of 0.3 m.

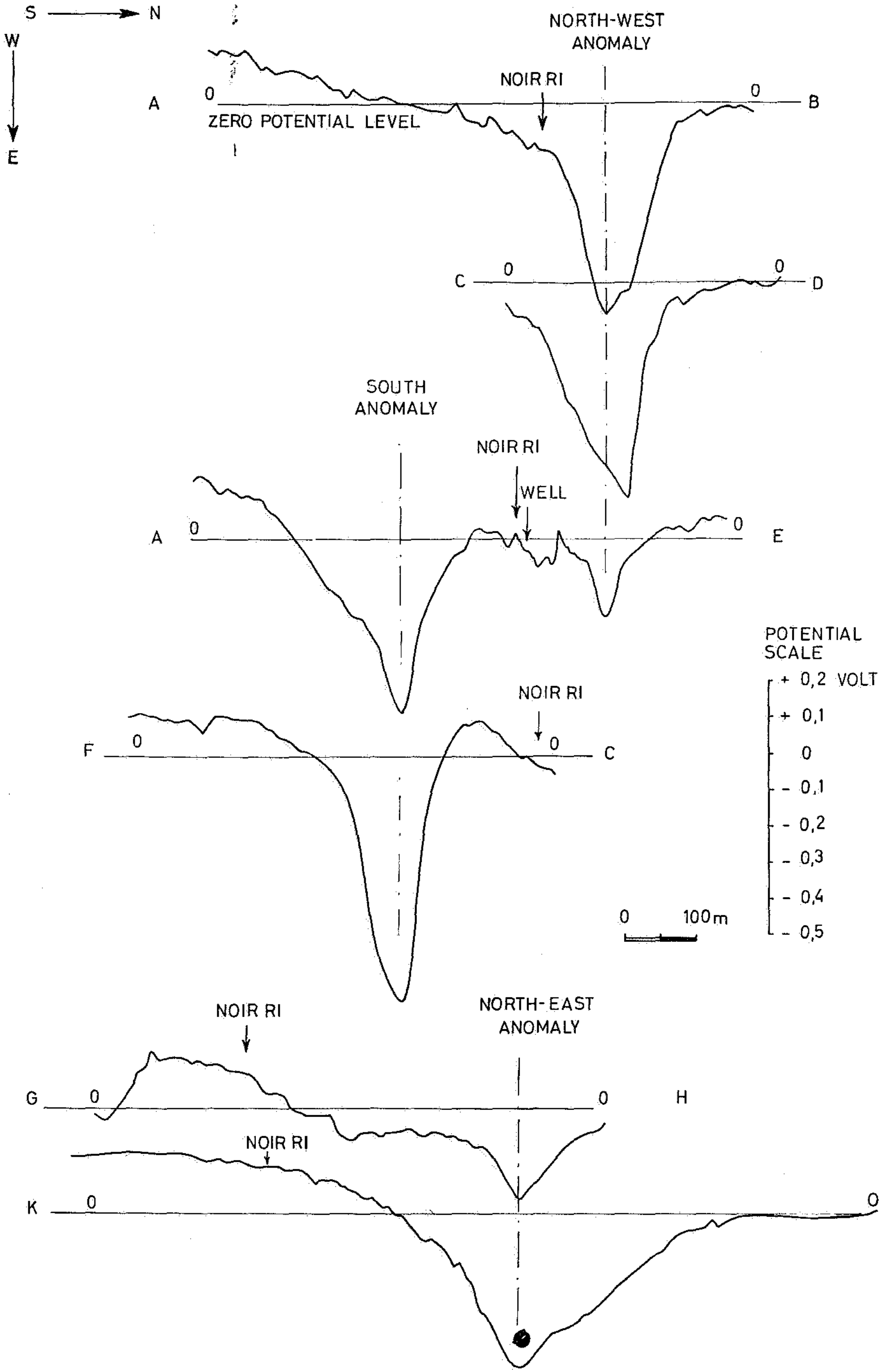

Fig. 3. Some characteristic S.P. profiles.

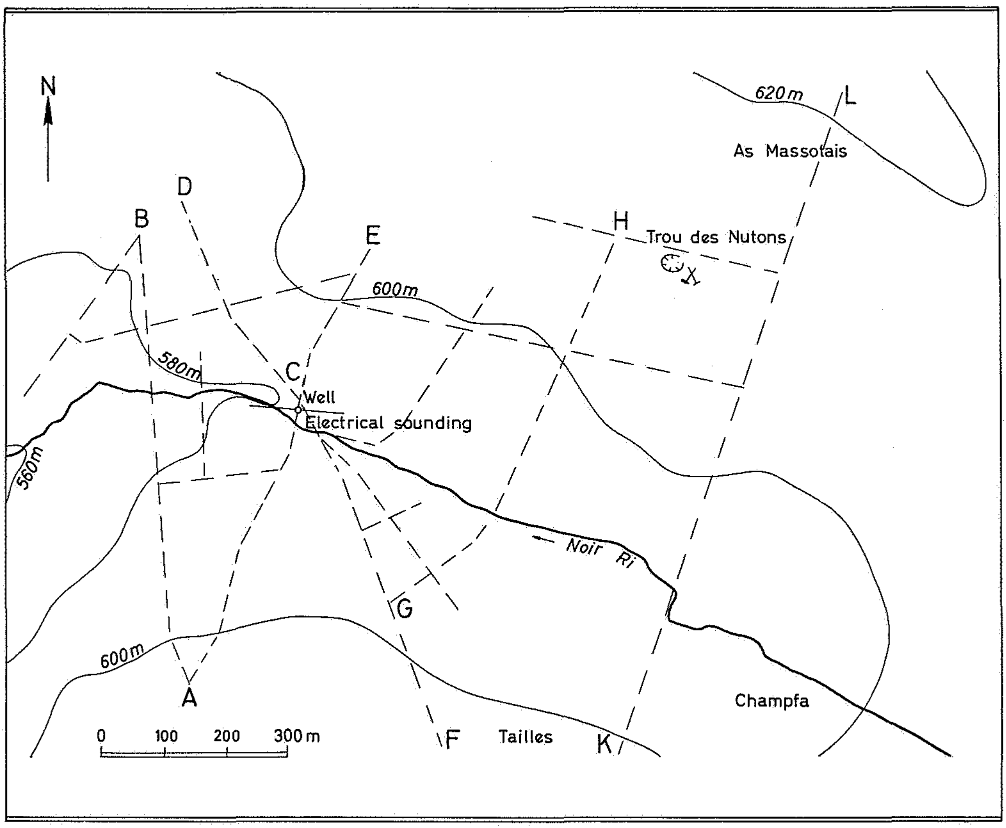

Fig. 4. Lay-out of S.P. profiles.

anomalies, of a total amplitude of 1134 mV, should deserve some attention. As an illustration, some of the largest S.P. anomalies reported in the literature are listed in table 1. The study of the S.P. mechanism by SATO and MOONEY (1960), from which three of the listed references (2, 3, 4) were taken, is probably the most detailed one published so far. Besides their own investigations, they reviewed about 150 papers dealing with S.P. near ore bodies.

Electrochemical origin of the main anomalies

The occurrence of negative S.P. anomalies of several hundreds of mV is generally bound to the presence of sulfide ore bodies or graphite mineralisations.

In opposition to many other authors who investigated S.P. phenomena, SATO and MOONEY disprove mechanisms involving direct oxydation of the top of ore bodies. They claim that potential differences producing electric currents in the ground originate by separate but simultaneous reduction of oxidizing agents near the surface, and oxidation of reducing agents at depth, beneath the water table. The ore body does not participate directly in either reaction, but serves as a bridging electronic conductor, transferring the electrons from the reducing agents at depth to the oxidizing agents at the top. Such reactions require a difference in oxidation potential (or Eh) of groundwater at different depths. In the weathering zone, the oxidation potential would mainly be controlled by the reduction mechanism of oxygen, whereas beneath the water table, the potential would probably be controlled by the oxidation-reduction equilibria of iron-rich minerals. Proposed half-cell reactions

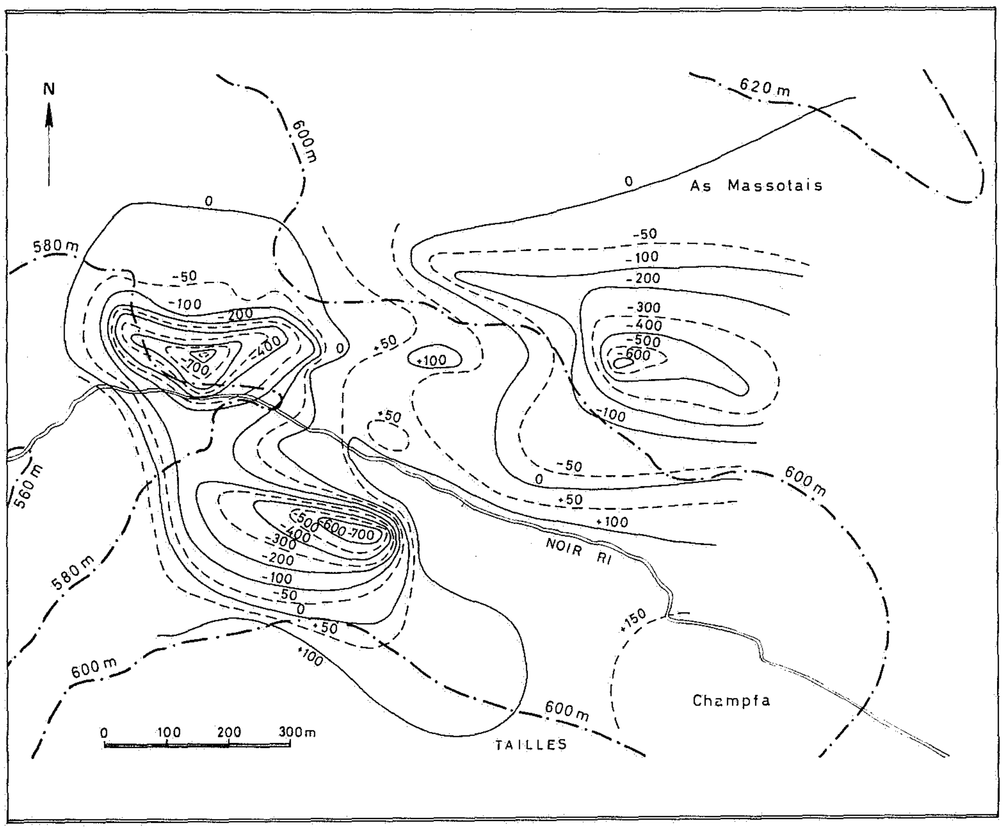

Fig. 5. Self-potential map.

participating in the self-potential mechanism in the wheatering zone are the oxygen-hydrogen peroxide couple and the ferric-ferrous ion couple, whereas dominant reactions beneath the water table would be the ferrous ion-ferric hydroxide couple and, to a lesser extent, the ferrous hydroxide-ferric hydroxide couple (fig. 6). Hydrogen peroxide is unstable and quickly decomposed by catalytic elements in solution (iron, manganese).

With the above theory, SATO and MOONEY are able to estimate the order of magnitude of the maximum potential differences available for the production of electric currents: 800 mV for graphite, 700 mV for pyrite.

From geometrical considerations, it appears that the maximum anomaly to be expected above such an ore body would amount to half the total potential difference. Compared to large anomalies reported in the literature (table 1), these theoretical estimates are rather on the lower side.

The Noir Ri anomalies are also quite larger than those theoretically estimated values. However, their occurence is bound to a combination of factors, all of them favorizing strong self-potential anomalies:

- black shales with graphite traces, an excellent electronic conductor (sounding 557/33)
- steeply dipping structures allowing a fast bridging of solutions at different depths
- high acidity of the water, issued from the raised bog of Champfa-Grandpassage (pH 3 to 5, COSAN 1969), favorizing the reduction of oxygen in surface waters
- abundance of iron and manganese mineralisations in the rocks of the Plateau des Tailles (catalytic agents for the decomposition of hydrogen peroxide)
- top of the conducting formation close to

TABLE 1. *Some of the largest S.P. anomalies*

Country	Author	Amplitude (mV)	Origin
Peru	PARKER GAY 1967	−1800	(alunite)
Norway	GENESLAY [1]	−1300	black shales
Japan	FUJITA 1926 [2]	−1300	—
Japan	SHIBATO 1949 [3]	−1000	graphite
India	DESSAU 1950	−1000	pyrite
India	DESSAU 1950	− 900	graphite
Peru	KRUGER & LACY 1949 [4]	− 700	alunite

[1] in LASFARGUES 1957
[2] [3] [4] in SATO & MONEY 1960

the surface (shallow soil cover, young topography with steep slopes).

It should be stated that none of these factors was not taken into consideration in SATO and MOONEY's theory. From this we are inclined to conclude that some other mechanism, not completely covered by the above theory, could be involved.

Structural interpretation of the main anomalies

Although some quantitative interpretation methods for self-potential anomalies have been proposed (DE WITTE 1948, YÜNGÜL 1950, MEISER 1962, PAUL 1965), we have not tried to apply them in a rigorous way on the Noir Ri survey. One of the reasons is purely technical: clear positive poles which could make a pair with any of the main negative anomalies are lacking. The location of the associated positive pole is one of the characteristic points used in the calculation procedures proposed by those authors. To a lesser extent, we were also influenced by the fact that the validity of these procedures had been subject to controversy (e.g. PARASNIS 1967).

Without rigorous calculations, it is however possible to make a fair qualitative estimation of the direction of dip and strike of the polarized bodies, based on the general pattern of equipotential lines.

The formation responsible for the S anomaly seems to dip to the north, with a strike of N 80° W. Roughly similar strike and dip values were observed on an outcrop in the bed of the Noir Ri, south of the drilling site.

The NW anomaly does not reflect a uniform preferential dip direction on all profiles; hence the polarized body is considered to be approximatively vertical. As to the NE anomaly, a slight skew to the north could be caused by a dip of the formation to the south. The directions of strike suggested by the elongation of both NE and NW anomalies are roughly similar, suggesting a possible west-east continuity of the conducting formation throughout the north slope of the basin. How deficient soil drainage conditions could have restricted the extension of the large negative anomalies is discussed in the next paragraph.

The general trend outlined above could correspond to a synclinal structure. The Noir Ri follows the axial plane of the fold, roughly striking ESE, before bending to the south. However, as these geological formations have been affected by two orogeneses (caledonian and hercynian), more complex structures could not be excluded.

The quasi linear western limit of both NW and S anomalies, together with the sharp bend in the flow direction of the Noir Ri on that

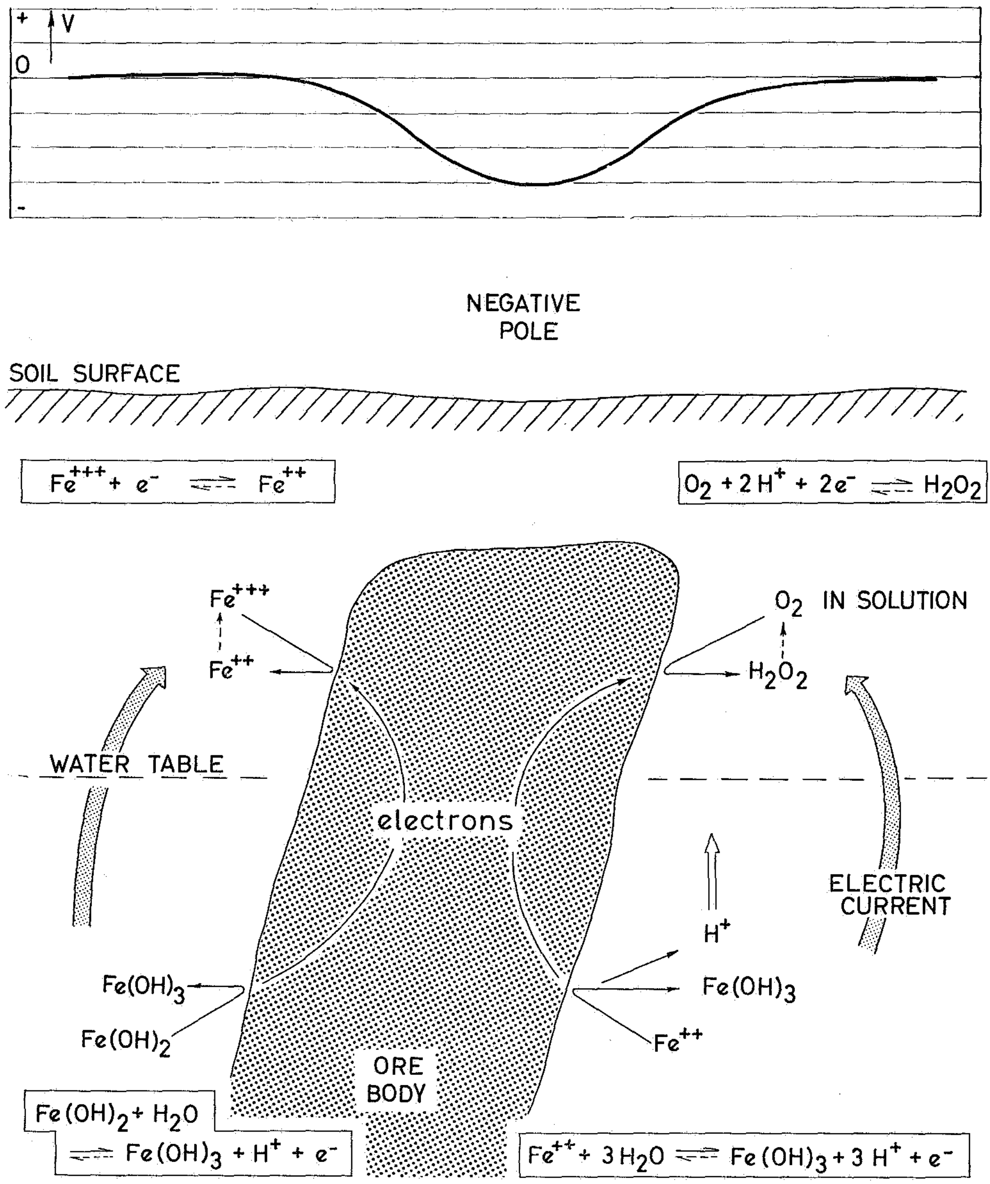

Fig. 6. Electrochemical S.P. mechanism, after SATO and MOONEY (1960).

spot suggest the presence of a NNW striking fault system. Such faults could have quite a local character and merely be the result of the strong contrast in mechanical properties between the sandy shales and the black shales. The latter rock type could act as a lubrifiant in a fault system. Intense microfolds and -faults were observed on the cores from the base of the sandy shales, close to the contact with the black shales (12-14 m).

The complete structural picture drawn from these interpretations is shown on figure 9.

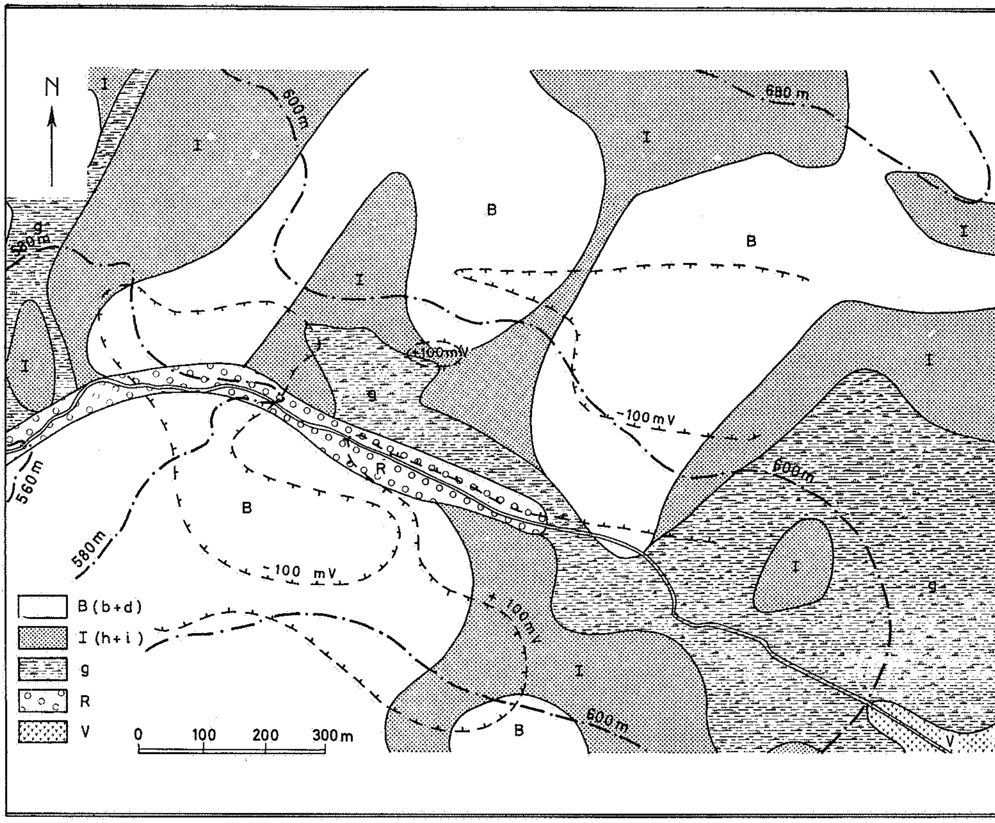

Fig. 7. Simplified soil drainage map of the Noir Ri basin, compiled after the soil map of Belgium (sheet 179 W, J. DECKERS 1958). Equipotential contours of + 100 mV and − 100 mV superposed.

Interference from soil drainage conditions

A soil drainage map was compiled for the Noir Ri basin (fig. 7) from the general soil map of Belgium, sheat Odeigne (179 W, J. DECKERS 1958). The determination of drainage class, characterised on maps by a letter symbol in accordance with the belgian soil survey system, is made by visual observation of characteristics of wetness (mottling, greyish base colours) and of the depth at which these characteristics are found (R. TAVERNIER & R. MARECHAL 1962).

For reasons of clearness, related drainage classes were grouped into complex units. Unit B covers mainly well drained soils (drainage class b), together with some imperfectly drained soils (class d) of minor extension. Unit I groups somewhat poorly drained to poorly drained soils, without reduced horizon (classes h + i). Class g characterises extremely poorly drained (reduced) soils with a permanent water table. Equipotential contours of + 100 mV and − 100 mV have been superposed on this drainage map.

Although soil mapping and S.P. survey in the Noir Ri basin were carried out quite independently, a striking similarity shows up between soil drainage pattern and distribution of S.P. anomalies. Large negative anomalies are exclusively found in areas with well drained soils and are bordered on several sides by zones with poor drainage. We could conclude from this relationship that, although the presence of large negative anomalies is bound to conductive mineralisations located in the bedrock, their continuity would mainly be ruled by superficial drainage conditions. As an example, we assume that the NW and NE anomalies are due to one and the same west-east striking formation, but that poor drainage conditions inhibited the electrochemical S.P. generation mechanism in the central part of it. A main inhibiting factor could be a lack of oxidizing agents (free oxygen in solution), required in SATO and MOONEY's scheme for the reduction reaction in the weathering zone.

If this relationship could be confirmed, the assessment of soil drainage class by a simple manual augering technique could prove a useful tool for a better understanding of the often puzzling distribution pattern of S.P. anomalies. As soil cartography is a one-man technique, exploration costs of a S.P. survey would not be significantly raised.

Hydrologic interpretation of positive anomalies

The potential map displays two distinct areas with positive anomalies exceeding + 100 mV. The first one, of rather limited extension, comes up on the north slope of the basin, between the NW and NE anomalies. The second one stretches in the south-east angle of the map, where it roughly coincides with the lowermost termination of the bog zone of Champfa-Grandpassage. In the central part of the survey area, it narrows and follows the bottom of the valley, closing between the NW and S anomalies.

In a first interpretation, it is possible to try to identify them with positive poles, associated with the main negative anomalies, in accordance with the concept of inclined dipoles. However, it is our opinion that the small N potential high is too distant from the big negative centers and that it really does not seem to form a pair with any of them. As to an eventual positive pole associated with the S anomaly, it could be found somewhere in the extended positive area covering the bottom of the basin, but it is doubtful that it could build it up alone. This suggests a generation mechanism for the positive anomalies, different from that adopted for the negative ones.

A quick inspection of the soil drainage map provides a hint towards a hydrological explanation. Both N and SE anomalies are mainly located in areas with poorly drained soils without reduced horizon (group I) which, downslope, turn to reduced soils (g). Another fact to take into consideration is the broad fan-like extension of the SE anomaly over the lowermost end of the bog of Champfa-Grandpassage.

Without being too affirmative, it is possible to associate these anomalies with streaming potentials. As the anomalies are positive, they correspond to a rising flow. Hence, some drainage class I soils in the Noir Ri basin would betray ground-water seepage zones. Such filtration zones would be responsible for the quasi permanent saturation of the lower-laying class g soils.

The origin of the large SE anomaly could be a groundwater flow seeping from underneath the Champfa-Grandpassage bog (fig. 8). The confining stratum in this case would be a low-permeability soil or soil horizon at the base of the peat. Seepage in the lower valley soils could become possible by the outwedging of this impermeable layer towards the bottom of the valley. Moreover, the higher pressure head in the aquifer in the lower part of the valley certainly plays a role too in a seepage mechanism. This head should be measured approximatively between the seepage area and the top of the bedrock beneath the Grandpassage bog (13 m), if the extension of the confining stratum is limited to the peat zone, or between the seepage area and still a higher zone of the Plateau des Tailles, if the confining layer is a soil horizon with larger extension. It should be pointed out that nearly all loamy soils of these high plateaus of the Ardennes are characterised by the presence of a so-called fragipan horizon, essentially a very compact loamy subsurface horizon which is very slowly permeable to water (J. DECKERS 1966; U.S. dept. of Agric., VIIth Approximation 1960). Besides, the presence of a confined aquifer beneath the base of a peat zone had already been observed by the author when a well was drilled in another bog of the Plateau des Tailles, the Fange de la Goutte. The proposed hydrologic interpretation has been combined with the structural interpretation in figure 9.

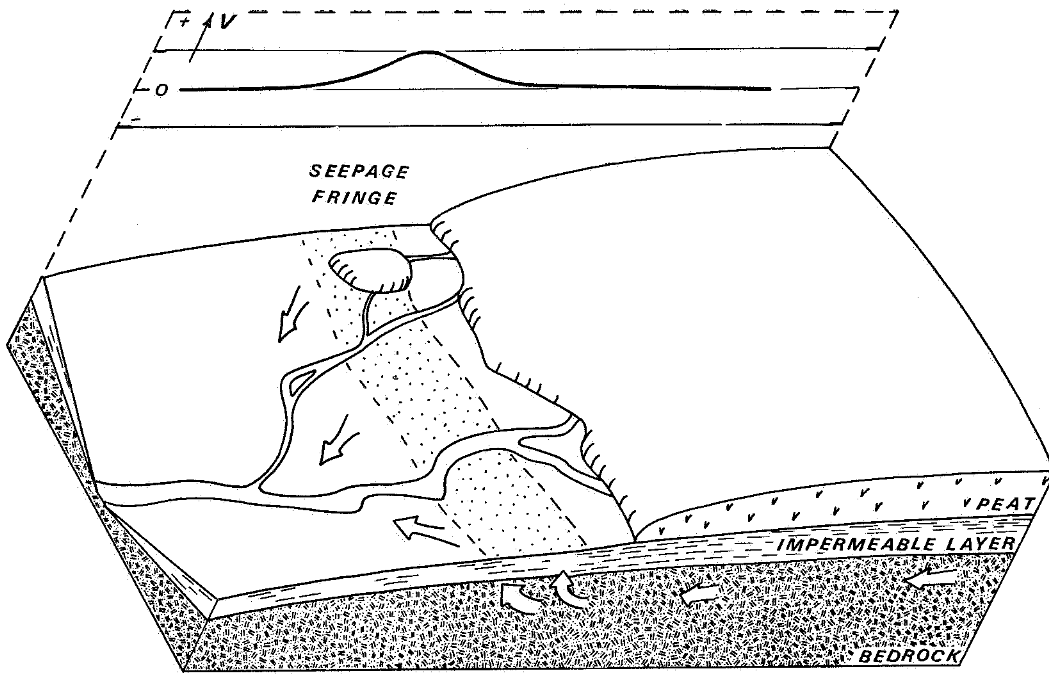

Fig. 8. Scheme illustrating the electrofiltration hypothesis for the generation of positive S.P. anomalies downstream the raised bog of Champfa-Grandpassage.

In order to check if the geohydrological conditions prevailing in the Noir Ri basin are able to yield self-potential anomalies of the order of magnitude of those measured, it is necessary to check the physical principles ruling the generation of streaming potentials in nature. The theory of streaming potentials has been developed by HELMHOLTZ (1879), SAXEN (1892), BIKERMAN (1932), NEALE (1946) and several other authors. The basic relation ruling streaming potentials is HELMHOLTZ's equation:

$$U = \frac{a\,\varepsilon\,\zeta\,h}{4\pi\,\sigma\,\eta\,l}$$

U = potential difference
a = electrode separation
ε = dielectric constant
ζ = Zeta potential
h/l = hydraulic gradient in the alignment of the electrodes (l = a if h is measured between the electrodes)
σ = conductivity
η = viscosity

Various authors, among them SCHRIEVER and BLEIL (1957), AHMAD (1964), SCHUCH and WANKE (1967, 1968, 1969) and OGILVY (1969), investigated streaming potentials on natural soil materials for their dependence from grain size, permeability, pressure head, electrolyte conductivity and some other parameters, both in the laboratory and in the field. Extrapolating some of these laboratory measurements (e.g. AHMAD 1964), we tried to make a rough estimation of the order of magnitude of streaming potentials, which could originate under conditions like those prevailing in the Noir Ri basin. The obtained values were generally quite higher than the measured ones (up to a tenfold). This could be caused by an overestimation of some factors, for instance of the pressure head. Smaller pressure heads than the assumed one (13 m) would already yield anomalies of an order of magnitude comparable to those measured. However, the inaccuracy in the estimation of several parameters (grain size, water conductivity, pressure

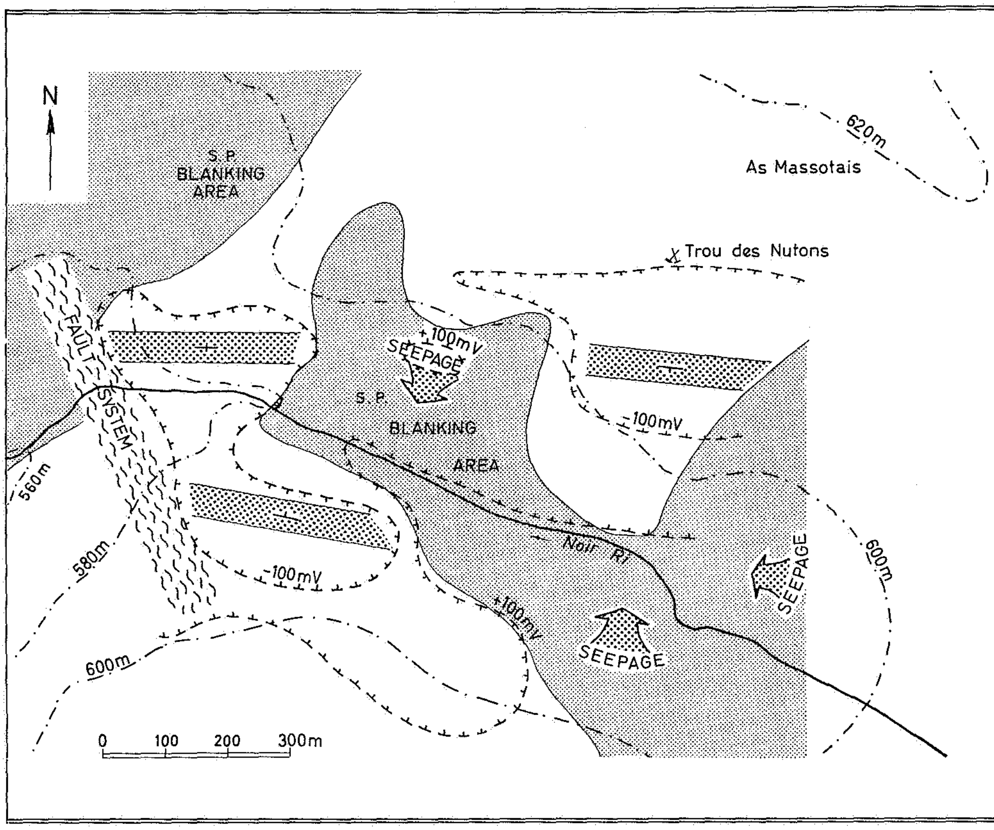

Fig. 9. Synthesis of the structural and hydrological interpretations for the Noir Ri anomalies.

head,...), as more on a level of principle, the risk inherent in all extrapolations of laboratory measurements to field conditions, make such quantitative estimations rather speculative.

Acknowledgment

The geoelectrical survey on the Plateau des Tailles was directed by Profs. Drs. R. MARECHAL and R. TAVERNIER, and it is a pleasure to acknowledge my debt to them. That survey formed a contribution to a hydrological research program coordinated by the « Centre pour l'Etude du Problème de l'Eau sur le Plateau des Tailles » (C.E.T.A.), and I wish to thank its director, Prof. Dr. J.-P. HARROY, for the hospitality kindly given during field work. Finally, Prof. S. SAXOV and Fil. Dr. D. MALMQVIST (Aarhus, Denmark) are gratefully acknowledged for valuable comments.

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