Self-potential signals associated with preferential ground water flow pathways in a buried paleo-channel.

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Self-potential signals associated with preferential ground water flow pathways in a buried paleo-channel

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[1] The flow of ground water in a buried permeable paleo-channel can be observed at the ground surface through its self-potential signature. We apply this method to delineate the Saint-Ferréol paleo-channel of the Rhone River located in Camargue, in the South East of France. Negative potentials, ~ -30 mV (reference taken outside the paleo-channel), are associated with ground water flow in this major sand-filled channel (500 m wide). Electrical resistivity is primarily controls by the salinity of the pore water. Electrical resistivity tomography and in situ sampling show the salinity of the water inside the paleo-channel is ten times smaller by comparison with the pore water of the surrounding sediments. Combining electrical resistivity surveys, self-potential data, and a minimum of drilling information, a 3-D reconstruction of the architecture of the paleo-channel is obtained showing the usefulness of this methodology for geomorphological reconstructions in this type of coastal environment. **Citation:** Revil, A., L. Cary, Q. Fan, A. Finizola, and F. Trolard (2005), Self-potential signals associated with preferential ground water flow pathways in a buried paleo-channel, *Geophys. Res. Lett.*, *32*, L07401,

1. Introduction

[2] The flow of water in a porous material is responsible for a measurable electrical field called the "streaming potential" positive in the direction of flow. These signals can be mapped using non-polarizing electrodes placed in contact with the ground [*Petiau*, 2000]. *Fournier* [1989] and *Birch* [1998] have shown that these self-potential (SP) measurements can be related to ground water flow in unconfined aquifers. It follows that preferential fluid flow pathways characterized by strong hydraulic transmissivities should have a typical electrical signature observable at the ground surface. However to the best of our knowledge, this methodology has never used in the field to map a sand-filled paleo-channel. In this paper, we provide a test of the SP method to delineate the position of a 500 m-wide paleo-channel of the Rhone River in Camargue, in the South-East of France. Applications of this work concern the delineation of gravel-belts and valley-fills in terms of economically significant ground water reservoirs and the monitoring of water quality in catchment areas, where altitude is just above sea level, in response to global climate changes and sea level rise.

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2. Experimental Background

[3] The flow of ground water through a porous soil is responsible for a polarization of charge due to the drag of the excess of electrical charges contained in the pore water, in the vicinity of the mineral surface. This phenomenon generates a positive electrical potential in the ground water flow direction. The strength of the resulting electrical potential is quantified by the streaming potential coupling coefficient C' in V m^{-1} [*Revil et al.*, 2004],

$$C' \equiv \left(\frac{\partial \psi}{\partial h}\right)_{\mathbf{j}=0} = \left(\frac{\varepsilon_f \rho_f g}{\eta_f \sigma_f}\right)\zeta, \tag{1}$$

where $\mathbf{j}$ is the total current density, h is the hydraulic head (in m), ψ is the electrical potential resulting from the flow of the pore water (in V), ε_f σ_f, ρ_f and η_f are the dielectric constant (F m^{-1}), the electrical conductivity (S m^{-1}), the mass density (kg m^{-3}), and the dynamic viscosity (Pa s) of the pore water, respectively, and ζ (in V) is the zeta potential, a key electrochemical property of the electrical double layer [*Revil et al.*, 2004]. The rhs of equation (1) corresponds to the so-called Helmholtz-Smoluchowski equation, which assumes that surface conductivity in the electrical double layer can be neglected in comparison with the electrical conductivity of the pore water. Under the same assumption, the electrical resistivity ρ is related to the electrical conductivity of the pore water σ_f by,

$$\rho = F/\sigma_f, \tag{2}$$

where F is the electrical formation factor.

[4] From equations (1) and (2), the electrical resistivity and the streaming potential coupling coefficient are both affected linearly by the salinity of the pore water. This dependency was tested by measuring both parameters for a set of cored specimens taken from the buried paleo-channel investigated below. The measurements were performed using the apparatus described in Figure 1a. The results are reported in Figure 1b. The streaming potential coupling coefficient is very sensitive to the salinity of the pore water as implied by equation (1). The higher the salinity is, the lower the streaming potential coupling coefficient. High resistivity values correspond to high values of the streaming potential coupling coefficient and therefore high value of SP signals if ground water moves under a gradient of the hydraulic head.

[5] From these laboratory measurements we expect that a permeable buried paleo-channel filled with fresh water would show a clear negative SP signal at the ground surface

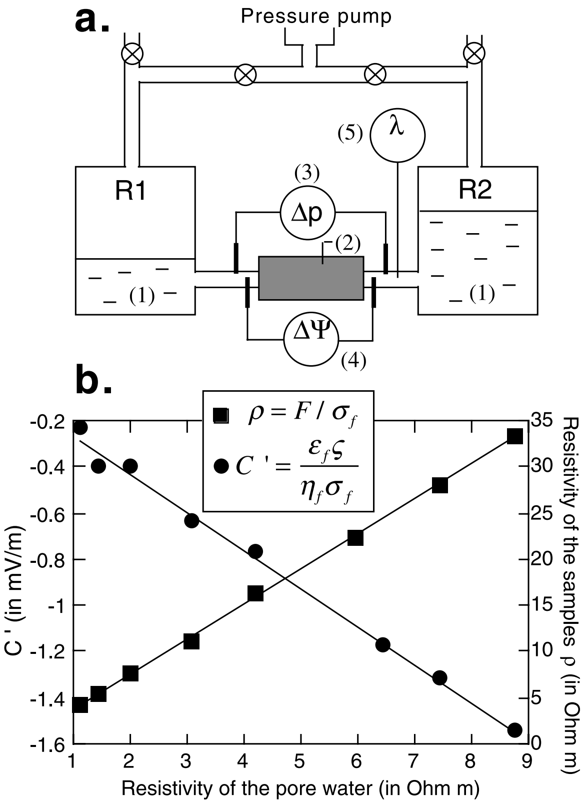

Figure 1. Measurements of the streaming potential coupling coefficient and the electrical resistivity of the core sample specimens. a. Sketch of the experimental setup (ZetaCad™). (1) Pore fluid reservoirs R1 and R2; (2) Sample tube; (3) Pressure sensors, (4) Voltage non-polarizable electrodes connected to an impedance meter, (5) measurements of the electrical conductivity of the electrolyte. The pressure difference between the two reservoirs is controlled with nitrogen gas. Water flows from one reservoir to the other through the porous plug and the difference of electrical potential is recorded at the two end faces of the porous plug. The streaming potential coupling coefficient is defined as the difference of electrical potential divided by the difference of pressure head between the two reservoirs. b. Streaming potential coupling coefficient (filled circles) and electrical resistivity measurements (filled squares) versus the resistivity of the pore water for various sand samples extracted from the buried paleo-channel investigated in this study (NaCl solutions, 21 ± 2°C). The electrical formation factor is equal to 3.8 ± 0.2 and the zeta potential is equal to −28 ± 3 mV.

relative to that measured at an arbitrary reference electrode placed in the surrounding sediments. Electrical resistivity tomography and few boreholes can be used to visualize the shape of the paleo-channel materialized by high resistivity values if the pore water of the surrounding sediments is saltier than the pore water infiltrating the buried paleo-channel.

3. Field Application

[6] Located on the South East of France, the Rhone river delta (Camargue) is one of the most important catchment in Western Europe. The area investigated here, Méjanes, is used for the culture of rice. It is located North West to the saline pond of Vaccarès (Figure 2b). This plain is formed mainly by fluvial deposits of an ancient Rhone channel called the Saint-Ferréol Channel (Figure 2c) that channels water from 5.500 BP to the end of the XVth Century.

[7] In principle, the salinity of the Méjanes area is high due to saltwater intrusion in the vicinity of the saline Vaccarès pond. However, the possibility to cultivate rice suggests that the salinity of the ground water is lower than just there around. This was locally confirmed by drilling and in situ measurements of the water conductivity (see below). In addition to these conductivity measurements, previous researchers relied on drill cores to map the subsurface lithology of this area. However the lack of extensive coring programs has been a clear limitation in the determination of lateral facies changes. This explains the emerging interest for geophysical methods to image the subsoil of these areas.

[8] Geophysical methods allow non-intrusive high resolution investigations of the ground. Electrical resistivity and induced polarization are sensitive to the presence of salty water and highly permeable drainage pathways [*Slater et al.*, 1997]. Electrical resistivity tomography was recently used by *Baines et al.* [2002] to determine the geometry of channel-belts and valley-fills. However, mapping the 3D structure of a large paleo-channel like the one investigated in this study is a very time consuming operation if only galvanometric resistivity and induced polarization data are used. SP measurements allow the coverage of a higher surface area in a shorter period of time.

[9] For the reasons described in section 2, fluid flow in a preferential fluid flow pathway, like a sand-filled buried

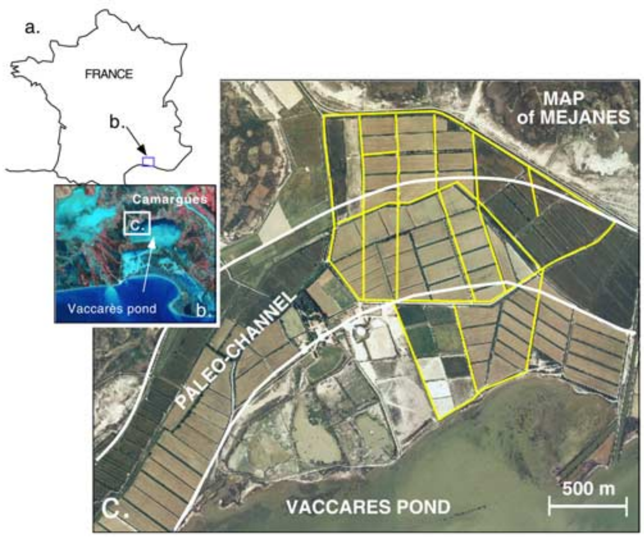

Figure 2. Location of the investigated area. a. b. The Rhone river delta (Camargue), one of the most important catchments in Western Europe, is located in the South-East of France, near Marseille. c. Méjanes is located to the North-West of the Vaccarès pond. The position of the SP profiles are indicated by the yellow plain lines. The average distance between the measurements is 20 m. The approximate position of the buried paleo-channel of the Rhone river is indicated by the white plain lines.

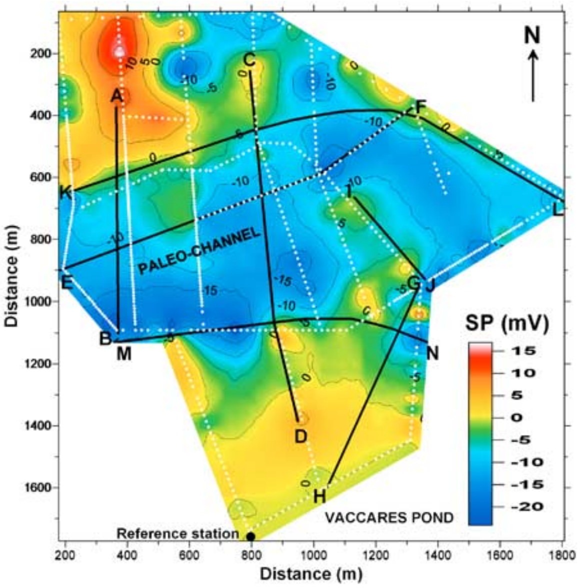

Figure 3. Self-potential (SP) map (in mV) with the position of the electrical resistivity profiles AB, CD, EF, GH, IJ, and GH. The fine gray line indicates the position of the SP profiles used to map the SP anomaly (the reference is located at the South of the map).

paleo-channel, should show a typical negative SP signature. Therefore we carried out an extensive campaign of SP and electrical resistivity measurements from March to April, 2004 at Méjanes. Over 700 SP measurements and 4000 electrical resistivity measurements were obtained in the area shown in Figure 2. Measurements were obtained along closed loops to reduce cumulative errors. The closure errors were redistributed over the stations to close electricaly the loops as imposed by Kirchoff's law [*Revil et al.*, 2004]. The SP map (Figure 3) is built relative to an arbitrary reference taken here along the coastline of the Pond of Vaccarès. Indeed, the high salinity of the pond water insures that the coastline provides a good equipotential that can be used as a suitable reference for the whole SP map. A marked negative SP anomaly of $\sim$$-$(15–30) mV underlines the position of the paleo-channel indicated by drillings (Figures 3 and 4).

[10] We collected also seven electrical resistivity profiles. A drillhole was also used to check the position of the channel (Figures 3 and 4). Acquisition of the resistivity data were obtained using the ABEM SAS-4000 apparatus, an electrode spacing of 5 m, the Wenner-α configuration for its good signal-to-noise ratio, and 64 stainless steel electrodes. Because of their length (generally > 500 m), the profiles were completed using a roll-along of the electrodes. Data were inverted with the robust inversion scheme of RES2DINV [*Loke and Barker*, 1996].

[11] Figure 4 shows a negative SP anomaly associated with the presence of the buried paleo-channel. In isothermal conditions, SP is the sum of three contributions (a) streaming potentials [*Fournier*, 1989], (b) diffusion potentials associated with salinity gradients, and (3) redox potentials [*Naudet et al.*, 2004]. We measured the redox potential at a depth of 1.6 m at different locations inside and outside the paleo-channel with a platinum electrode against a standard Ag/AgCl electrode, and then converted to the normal hydrogen scale with temperature correction. We found the redox potential in the range $-$(220–270) mV with no marked difference between the materials filling the paleo-channel and the surrounding sediments. Diffusion potentials associated with salinity gradient would create positive SP anomalies of few millivolts. These contributions can therefore be safely neglected. Only the streaming potential can explain the observed SP anomalies.

4. Interpretation

[12] An average value of the electrical formation factor F of the sediment filling the paleo-channel is equal to $\sim$4 ± 1 (Figure 1b). Electrical resistivity tomography indicates that resistivity of the sediment in the buried paleo-channel in the range 12–40 Ωm. Taking $\rho_f = \rho/F$ yields a resistivity of the pore water inside the buried paleo-channel in the range 3–10 Ωm. This range corresponds to a pore water conductivity in the range 1–3 mS cm^{-1} (note that geophysical measurements were performed during the non-irrigated period). In situ measurements, collected during 3 years from 2002 to 2004 at a depth of 1.6 m inside the paleo-channel, yield a pore water conductivity equal to 1 mS cm^{-1} during the irrigated period and 2.5 mS cm^{-1} during the non-irrigated period. This is consistent with the range of values given above.

[13] Electrical resistivity tomography indicates that resistivity of the sediment outside the buried paleo-channel is in the range 0.4–1.2 Ωm. Taking the same relationship as above and the same formation factor as a rough approximation, the resistivity of the pore water is in the range 0.1–0.4 Ωm, which is on the order of magnitude of resistivity of the sea water (0.2 Ωm at 20°C). So the "fresh" water flowing along the buried paleo-channel is approximately ten time less saline than the pore water contained in the surrounding sediments.

[14] Inside the paleo-channel, the streaming potential coupling coefficient is equal to -1.2 ± 0.4 mV m^{-1} based on the range of values for the resistivity of the pore water

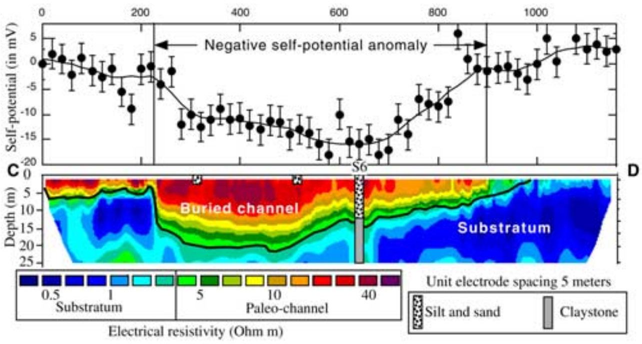

Figure 4. Electrical resistivity tomography (profile CD, Figure 3) and SP signals measured at the ground surface with Petiau electrodes with a spacing equal to 20 m. The SP anomaly ($\sim$$-$15 mV with a reference taken arbitrarily at the left-hand side of the profile) is correlated with the presence of the buried paleo-channel observed on the electrical resistivity tomography and borehole information (Hole S6). The error bars correspond to the mean standard deviation recorded for these measurements.

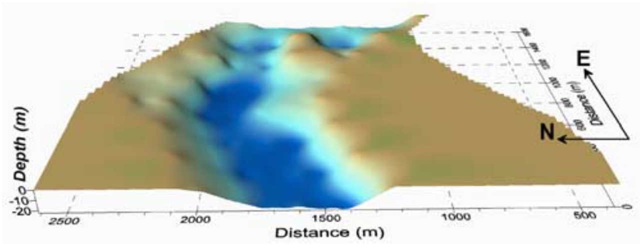

Figure 5. 3-D reconstruction of the architecture of the buried paleo-channel Resistivity data (using the threshold resisistivity value, 4 Ωm, determined in Figure 3 from the drilling information to get the depth of the channel), self-potential data (we use the potential contour line −5 mV to get the contour of the channel), and drilling information (Figure 4) are kridged in Surfer. The boundary on the righ-hand side of the picture corresponds to the coastline of the Vaccarès pond. Vertical magnification 1:5.

(3–10 Ωm) and the laboratory data reported Figure 1b. This is in the range of values usually reported in the literature for fresh ground water flow. At the opposite and according to Figure 1b, the magnitude of the streaming potential coupling coefficients in the surrounding sediments is <0.2 mV m^{-1}, so much smaller than inside the paleo-channel and can be neglected. Therefore the paleo-channel is characterized by a negative SP anomaly with respect to a reference taken outside the paleo-channel. This is explained because of (1) the high hydraulic transmissivity of the paleo-channel, (2) the high value of the streaming potential coupling coefficient in the paleochannel, and (3) the fact the hydroelectric coupling generates positive electrical signals in the direction of ground water flow. The threshold −5 mV coincides well with the lateral boundaries of the paleo-channel.

[15] In summary, the SP method allows to delineate the contours of the buried paleo-channel and is sensitive to the fact that the paleo-channel is still a preferential groundwater flow pathway while resistivity tomography provides the depth of the paleo-channel using the threshold value shown Figure 4. Both type of complementary geophysical information plus drilling information are used to reconstruct the 3-D shape of the paleo-channel using the kriging procedure of Surfer (Figure 5). This indicates the usefulness of these geoelectrical methods for geomorphological reconstruction of paleo-channels.

5. Concluding Statements

[16] The SP method is used to delineate preferential ground water flow pathways of low salinity pore waters in a saline coastal environnement. The understanding and the monitoring of these flow pathways in catchment plains, where altitude is just above the sea level, is crucial to foresee the potential evolution and the impact over the entire area of both global climate changes and sea level rise. The site of Méjanes in Camargue has been used to test a new methodology combining SP data and electrical resistivity cross-sections in the purpose to reconstruct the 3-D architecture of a buried (sand-filled) paleo-channel of the Rhone river. The SP method is sensitive to ground water flow inside the paleo-channel with an anomaly of ∼−15 mV. This method provides a cheap and efficient way to delineate the boundaries of the channel while electrical resistivity and drilling information are used to visualize the depth of the paleo-channel. The next step will be to combine induced polarization, SP, and electrical resistivity measurements to reconstruct the 3D Darcy velocity of groundwater flow inside such a ground water preferential fluid flow pathway.

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