Journal of Applied Geophysics 153 (2018) 47–63

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Exploration of buried carbonate aquifers by the inverse and forward modelling of the Controlled Source Audio-Magnetotelluric data

Franjo Šumanovac *, Jasna Orešković

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, Croatia

ARTICLE INFO

Article history:
Received 19 October 2017
Received in revised form 28 March 2018
Accepted 7 April 2018
Available online 11 April 2018

Keywords:
CSAMT
Groundwater
Carbonate aquifer
Forward modelling
Inversion

ABSTRACT

On the selected cases, Gotalovec in the area of Pannonian basin and Baška in the Dinaridic karst area, that are representing a common hydrogeological model in both regions of Croatia, CSAMT data together with data of other geophysical methods (electrical resistivity tomography, electrical sounding and seismic reflection) enabled the definition of a reliable prognostic geological model. The model consists of carbonate aquifer which underlies an impermeable thick package of clastic deposits. There are great variations of the dolomitic aquifer depths in the Gotalovec area due to strong tectonic activity, while in the Baška area depth changes are caused by the layer folding.

The CSAMT method provides the most complete data on lithological and structural relationships in cases of hydrogeological targets deeper than 100 m. Based on the presented models we can conclude that the CSAMT method can provide greater exploration depth than electrical resistivity tomography (ERT) and can be considered as a fundamental geophysical method for exploration of buried carbonate aquifers, deeper than 100 m. But, the CSAMT research may demonstrate its advantages only in the case of very dense layout of CSAMT stations (25–50 m), due to the greater sensitivity to noise in relation to resistivity methods. Interpretation of CSAMT data is more complex in relation to resistivity methods, and a forward modelling method sometimes gives better results than an inversion due to possibility of the use of additional data acquired by other geophysical methods (ERT, electrical sounding and seismic reflection). At greater depths, the resolution of all electrical methods including the CSAMT method is significantly reduced, and seismic reflection can be very useful to resolve deeper lithological interfaces.

1. Introduction

Magnetotelluric method (MT-method) has been applied for a long time for deep geological investigations, mainly geothermal and hydrocarbon investigations at depths of up to 10 km (e.g. Vozoff, 1972; Volpi et al., 2003; Spichak and Manzella, 2009), but also in very deep investigations of the Earth's crust and the lithospheric mantle which applies to depths up to 100 km (e.g. Pous et al., 1995; Unsworth et al., 2004; Semenov et al., 2008). It has only been used in recent decades in relatively shallow investigations in engineering geology and hydrogeology studies by the development of the method version which can use high frequency range responsible for near surface targets. These methods have been called Controlled Source Audio-Magnetotellurics (CSAMT) and Controlled Source Radio Magnetotellurics (CSRT). The methods can contribute to better determination of near surface geological relationships (Ismail et al., 2015; Pedrera et al., 2016).

On the other hand, electrical resistivity tomography (ERT) can be considered as the most recent method in near surface geophysical explorations (Dahlin, 1996; Loke and Barker, 1995), and its introduction has significantly advanced geophysical research. In the beginning the method was applied for shallow engineering geology investigations, but soon after it was applied in hydrogeological investigations, up to a depth of 100 m. Results of the first applications showed that the ERT can provide for a reliable predicted geological model, especially in the case of complex geological models, where the geological models of karstic terrains certainly belongs (Šumanovac and Weisser, 2001; Šumanovac et al., 2003). Besides, the karstic terrains are characterized by difficult conditions of field measurement. Results of many investigations in the karstic region of Croatia in the framework of groundwater research forced the conclusion that ERT has been considered to be the fundamental method in karstic hydrogeological investigations (Terzić et al., 2007; Vlahović and Šumanovac, 2015). The other geophysical methods, especially the seismic ones, are used in order to solve specific tasks and reduce the ambiguity of geophysical interpretation (Engelsfeld et al., 2008, 2011). The main reason for such application lies in the fact that resistivity methods involve the entire volume of

* Corresponding author at: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, HR-10.000 Zagreb, Croatia.
E-mail address: franjo.sumanovac@rgn.hr. (F. Šumanovac).

https://doi.org/10.1016/j.jappgeo.2018.04.007
0926-9851/

rock; based on the measured rock resistivity, and data about rock type and rock condition (whether it is compact, fractured or porous) can be obtained.

Electrical tomography is also applied to solve geological models in sedimentary basin. However, in the case of aquifers composed of thin sandy or gravelly layers, the other geophysical methods should be applied, especially seismic reflection, to determine a reliable predicted geological model (Šumanovac, 2006).

Standard equipment for ERT is efficient up to depths of about 100 m, but in the case of deeper targets in hydrogeological and geothermal investigations, ERT is not usually carried out because the field equipment would be too expensive and impractical. The tomographic profiles should be very long to reach deep targets, and there is often not enough space to set such long profiles. Length of the profiles could be often 800 m only, which means the depth penetration of 130 m in the middle of the profile.

Deeper hydrogeological investigations seek depth penetration of several hundred meters, and geothermal investigations even more than 1 km. In such cases, standard ERT cannot be applied in an economical and routine way, so other geophysical methods should be considered. The use of CSAMT can provide greater depths of research, as well as good space sampling and relatively dense measurements. A common hydrogeological model, which can be found in both main regions in Croatia, Pannonian basin and Dinarides (Fig. 1), can be solved by the CSAMT method. The carbonate aquifer is underlying an impermeable package of clastic deposits. The main goal is to define as precisely as possible the carbonate-clastic interface which will enable determination of optimal exploratory borehole positions. Two characteristic examples of groundwater investigations carried out in the Pannonian basin and Dinarides in Croatia are shown. The results achieved by the CSAMT method were correlated with data obtained by other geophysical methods, seismic reflection and electrical resistivity tomography, for comparison and verification. The main disadvantage of the CSAMT method compared to the direct current methods is greater sensitivity to urban and surface noises, which is especially prominent in urban environments and in the vicinity of electrical infrastructural facilities.

2. Geological setting

The targets of geophysical explorations in Croatia are often carbonate rocks that underlie clastic deposits. Carbonate rocks, Triassic dolomites and Jurassic and Cretaceous limestones and dolomites, may be tectonically fractured and weathered and are therefore permeable and as such act as aquifer. Clastic sediments above them consist mainly of impermeable clay, shale and marl, which are insulating rocks. This model is found in both geological regions in Croatia, in the Pannonian Basin and the Dinaridic karst area (Fig. 1). In the Dinarides clastic deposits are usually Eocene flysch sediments. Although they may contain permeable rocks such as sands, sandstones and carbonates, they are in a package of impermeable rocks, clay and marl, so the entire package acts as an impermeable barrier. Two representative locations are selected in order to analyse the possibilities of CSAMT method in groundwater research: Gotalovec in the Pannonian Basin and Baška on island Krk that belongs to the External Dinarides.

2.1. Gotalovec area

The first study area - Gotalovec, is located in the north-western Croatia, at the foot of Mount Ivančica (Fig. 1). The geological model in this part of Croatia consists of Quaternary and Neogene sediments (Miocene layers), and Cretaceous volcanoclastic rocks ($K_{1,2}$) which discordantly lay on a surface made of Upper and Middle Triassic dolomites (T_3, T_2), Šimunić et al. (1982; Fig. 2). These dolomites were exposed to intense tectonic activities in several stages during geological history.

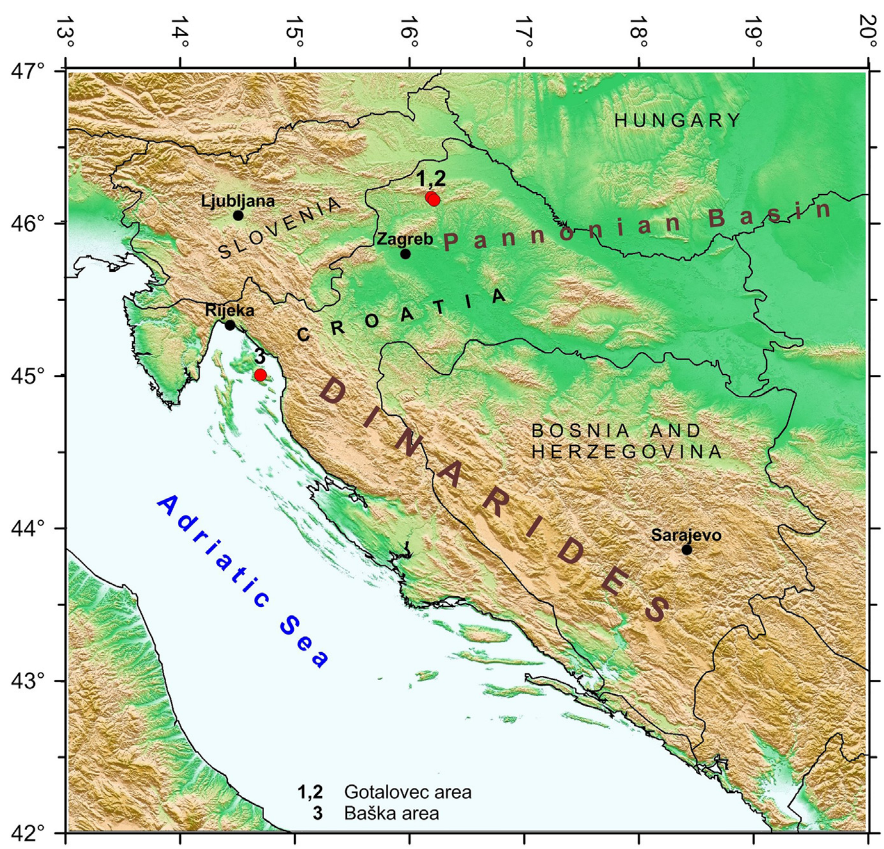

Fig. 1. Positional map of the surveys. Locations 1 and 2 belong to Pannonian basin, while location 3 belongs to the Dinarides. 1 – position of the profile P-1 at Gotalovec, situated in a hilly area; 2 – position of the profile P-2 at Gotalovec, situated in a valley; 3 – position of the profile P-3 on karstic island Krk.