Geothermal resource in a foreland environment: the Santa Cesarea Terme thermal springs (Southern Italy)

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ABSTRACT

Carbonate aquifers, located in foreland tectonic settings, could represent important thermal water resources outside the volcanic areas, supplying spas or geothermal installations. Thermal springs constitute so the discharge areas of the deep marine and continental groundwaters flowing within these carbonate aquifers whose hydraulic conductivity and the relevant geothermal fluid migration are strictly controlled by both the discontinuity network and the karst processes involving the foreland environment. An example of these springs occurs along the south-easternmost portion of the Apulia region (Southern Italy) where some sulphurous and warm waters (22-33 °C) flow out in partially submerged caves located along the coast, thus supplying the spas of Santa Cesarea Terme.

1. INTRODUCTION

The sulphurous and warm waters of Santa Cesarea springs are known from ancient times (e.g. Aristotle in IV century BC). They flow out along a well defined, 500 m-long, coastal sector of the Salento peninsula, which is part of the Apulia carbonate platform, (i.e. the foreland of the Apennines-Dinarides orogeny; Ricchetti et al., 1988; Fig. 1), consisting of Jurassic-Cretaceous limestone and dolostone, over 5 km-thick in the study area. This succession rests above Late Triassic evaporites (Burano Fm), and is unconformably overlain by Cenozoic 1 calcareous successions with stratigraphic lacunae. Offshore, the carbonate sequence underlies a Quaternary succession, up to 500 m thick, deposited in the foredeep of the Dinaric chain (Fig. 1).

Some hypotheses about the origin of these warm waters have been proposed in the literature (Zezza, 1980, Calò et al., 1983, 1995, Maggiore and Pagliarulo, 2004), but several uncertainties still exist.

The Santa Cesarea Terme territory is one of the pilot sites of the Vigor Project (Evaluation of the geothermal potential of the regions of convergence), promoted by the Italian Ministry of Economic Development and National Research Council. The area has been selected in order to define the conceptual model of the geothermal resources and the origin of the thermal springs.

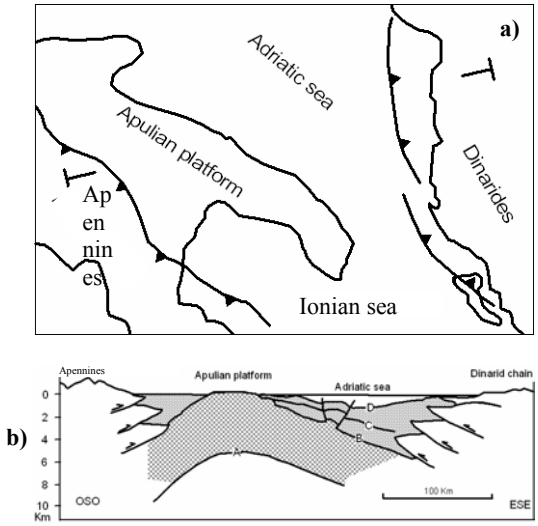

Figure 1: Structural sketch map of the Adriatic Sea and its surroundings (a) and simplified geological section through the Apulian foreland (b), modified from Moretti and Royden, 1988) - Explanation of boundaries: A. base of the Mesozoic units; B. top of the Mesozoic units, C. top of the Tertiary units, D. top the Quaternary deposits.

Detailed geological, morphological and hydrogeological surveys, including geo-electrical prospecting, and chemical and isotopic analyses of both groundwater and seawater have been carried out. In particular, stable isotopes ($\delta^{18}O$, δD) were used to define the origin of the thermal waters and the

recharge mechanism of the geothermal systems while the unstable isotope (^3H) was determined for estimating the age of the thermal waters. Further, well discharge measurements, well loggings, multi-parameters spring automatized measurements, and cave explorations have been accomplished in order to define the conceptual model of this low temperature geothermal resource.

All the data have been analysed to improve the knowledge of the groundwater flow system, thus assessing the possibility of using low-temperature geothermal fluids to fulfil the thermal needs of the town of Santa Cesarea Terme.

2. GEOLOGICAL SETTING

The Santa Cesarea Terme area is located along the south-eastern coast of the Salento peninsula (Fig. 1), a carbonate plateau defined by a wide, WNW–ESE trending, antiform structure, dissected by a series of extensional and strike-slip faults (Tozzi, 1993). Starting from the Early Triassic, the area was part of the Apulia platform palaeo-domain, characterized by shallow-water carbonate sedimentation (Mostardini and Merlini, 1986). Since Cretaceous times, the Salento peninsula experienced a series of alternating transgression and regression phases, giving rise to a succession characterized by lacunae and unconformities. In particular, during the Middle Pleistocene, the area underwent a severe regional uplift (Doglioni et al., 1994).

As shown in the geological map of Figure 2, the *Altamura Limestone* represents the calcareous bedrock at Santa Cesarea Terme, and consists of, from the bottom upward: Upper Cretaceous, well-bedded, peritidal dolomitic limestone; Late Eocene-Early Oligocene coral reef limestone, belonging to the *Castro Limestone* (Fig. 2); locally overlaying the Cretaceous formation through a marked angular unconformity (Bosellini et al., 1999; Bossio et al., 2005). Locally, both *Altamura Limestone* and *Castro Limestone* are unconformable overlain by the bentonic foraminifer-bearing Oligocene calcarenite (*Porto Badisco Calcarenites* in Fig. 2) and by the Messinian poorly bedded white calcarenite (*Andrano Calcarenites*). The younger formations cropping out at Santa Cesarea Terme are the *Uggiano La Chiesa Formation* (Middle Pliocene-Lower Pleistocene) and the *Salento Calcarenites* (Pleistocene), as depicted in Figure 2. The first is mainly made of yellow calcarenites while the latter consists of massive to poorly bedded, weakly cemented calcarenites, related to a slope environment, as testified by the presence of slumpings and submarine slides. The offshore equivalent of the *Salento Calcarenites* are well imaged in the seismic lines and form a series of prograding units settled during a forced regression (Aiello and Budillon, 2004).

The described carbonate successions (from Cretaceous to Pleistocene) are exposed and unconformably covered by continental units represented by red clays (residual deposits of karst processes) and different generation of talus deposits. In particular, the intense role of karst processes affecting the carbonate platform since Pleistocene has to be remarked. The karst landforms appear to be structurally controlled in the whole studied area.

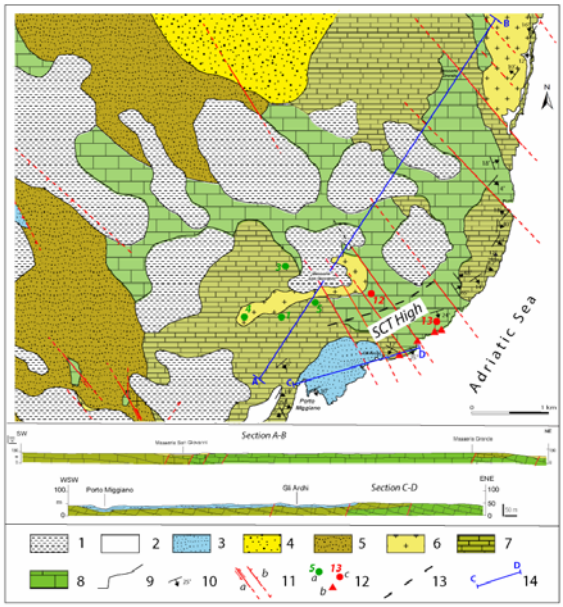

Figure 2: Simplified geological map of the studied area. Legend: 1) red clays, 2) talus deposits, 3) *Salento Calcarenites*, 4) *Uggiano La Chiesa Formation*, 5) *Andrano Calcarenites*, 6) *Porto Badisco Calcarenites*, 7) *Castro Limestone*, 8) *Altamura Limestone*, 9) stratigraphic contact, 10) strata attitude, 11) fault (a-transtensional, b-normal, dashed when inferred), 12) water sampling sites (a-cold well, b-thermal well, c-thermal spring), 13) geo-electrical profiles, 14) trace of the geological sections shown in the figure.

Several extensional and transtensional structures, with the related extensional jogs and pull-apart features, have been recognized (Fig. 2). They are mostly represented by NW-SE faults (Fig. 2), with associated structures, and by SW-NE, E-W and N-S faults. Cross-cutting relationships reveal also that the younger and dominant structures are represented by NW-SE transtensional faults, which offset Quaternary continental breccias (Santaloia et al. in prep.). Moreover, the NW-SE faults had a strong control in the development of the main karst landforms (doline, karst valley and so on) identified in the studied territory.

In some cases, all the described tectonic lineaments are responsible for the exhumation of the deeper stratigraphic levels recognised within the carbonate successions. The village of Santa Cesarea Terme, including the thermal springs, is located on a structural high (*Santa Cesarea Terme High* depicted as *SCT High* in Fig. 2), consisting of Meso-Cenozoic limestones (*Altamura Limestone* and *Castro*

Limestone formations) bordered by NW-SE structures. The structural high and the main bounding faults can be also observed offshore in a series of SW-NE oriented seismic lines, analyzed during the Vigor Project. The younger formations, belonging to the Paleogene-Quaternary portion of the studied sedimentary successions, laterally confine the *SCT High* which resulted to be the most structurally damaged zone of the whole studied territory (Fig. 2; Santaloia et al. in prep.).

The thermal wells and springs are located within this most damaged portion of the territory (Fig. 2). In particular, the caves where the thermal springs flow out are positioned along the NW-SE fault damage zones.

The damage zone is also characterized by a strong variability of the resistivity of the geo-electrical units recognized at depth, down to 180 m below ground level. For instance, fractured rocks with low resistivity values (lesser than 1000 ohm*m) have been found within the zone crossed by a thermal well (see the combined electrical resistivity tomography in Figure 3).

3. HYDROGEOLOGICAL FEATURES

In the studied territory the groundwater flows within deep and shallow aquifers. The deep aquifer occurs within the intensely fissured and karstified *Altamura Limestones*. It is of variable porosity and permeability, consisting in many places of well developed cavernous intervals separated by zones of lower permeability, which act as confining layers.

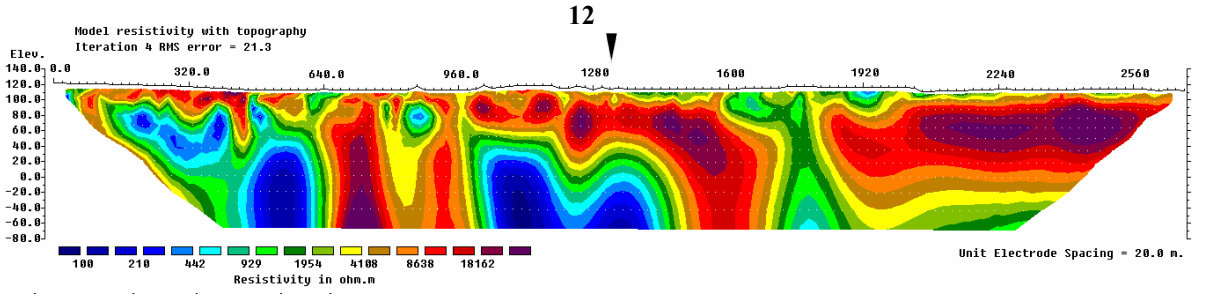

Figure 3: Combined electrical resistivity tomography (the trace of the profile is shown in Figure 2)

Therefore this deep aquifer is predominantly unconfined and phreatic, especially nearby the coast; otherwise it becomes confined either where impermeable strata occur within the carbonate successions or the top of the sequence, located closely or below the sea level, is covered by Quaternary impermeable deposits. Figure 4 shows the map of the potentiometric surface related to the deep unconfined aquifer, characterised by fresh groundwater. The shallow and phreatic aquifers, of limited extension, are located within the Neogene deposits. Usually they occur in topographically depressed areas, where Quaternary sands and calcarenites overlie impermeable clays formations.

Belonging to a coastal area, the deep groundwater, which top is located almost at the sea level, is involved in saltwater intrusion, with the salt-fresh water interface at some meters below the sea level moving inland. Therefore the deep fresh groundwater has been intercepted only some meters above the sea level (Fig. 4). Locally, where the thermal wells are, the piezometric level has been measured at some meters above the ground level.

As shown in Figure 4, the deep cold groundwater flows from the recharge inland areas to the discharge coastal areas, where several coastal springs drain the groundwater along preferential flow paths. The hydraulic heads resulted to decrease around 1,5 m moving towards the coast in South-East direction.

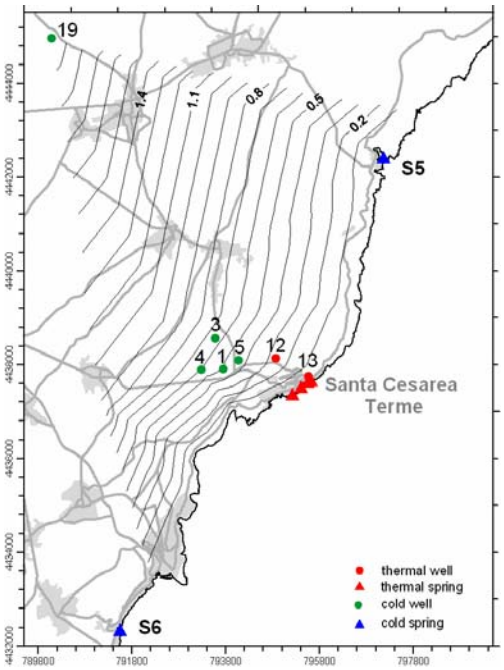

Figure 4: Potentiometric surface of the deep limestone aquifer, characterized by cold groundwater.

3.1 Field and laboratory data

Temperature, specific electrical conductivity, dissolved oxygen, redox potential, pH, alkalinity of waters have been determined in the field. Cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}, NO_3^{-}) were analyzed by means of ion chromatography (IC) methods. Minor and trace elements were determined by inductively coupled plasma mass spectrometry. Values for $\delta^{18}O$, δD and ^{3}H were obtained by mass spectrometry. The overall precision of the analyses based on major ions is within 5%. Data processing was carried out using the PHREEQC software. Location of the sampling points is shown in Figures 2 and 4.

The highest temperatures (22°-33° C) of the waters have been measured in some wells (thermal wells in Figs. 2 and 4) located in a narrow area not far from the coastal sector where the thermal springs develop (Figs. 2 and 4). Some meters from these thermal wells, the groundwater temperature decreases reaching the typical values of the deep Salento aquifer, that is about 18-19°C (Figs. 2 and 4). The thermal groundwater has higher total dissolved solids (e.g. 58000 mg/L) with respect to the fresh groundwater (generally up to 500 mg/L).

The major constituents are plotted in the Langelier-Ludwig diagram shown in Figure 5. The thermal waters are characterised by high values of alkaline ions (Na^{+}- K^{+}), higher than those measured for the seawaters. Moreover, they show high content of chloride ion (Fig. 5). High contents of alkali earth metal ions (Ca^{2+}-Mg^{2+}) have been found for the fresh groundwater (sample 1 in Fig. 5), which displays the typical composition of the groundwater flowing within the deep aquifer within the Salento peninsula (Fidelibus and Tulipano, 1986). The other cold-water samples (19, 5, 20, 3, 4 and 29 in Fig. 5) are a mixture of fresh groundwater and seawater.

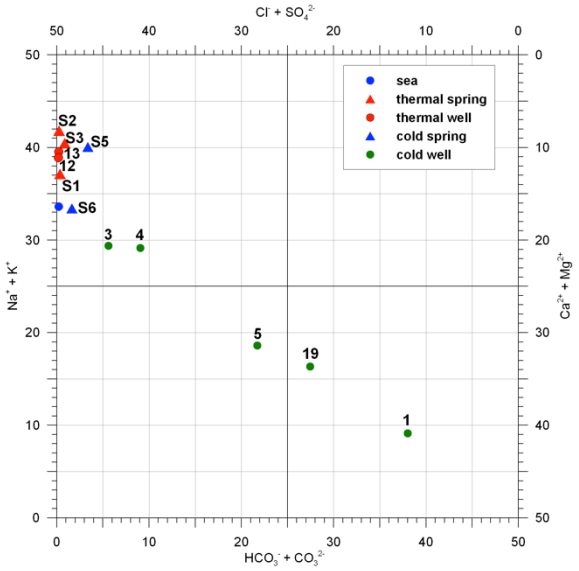

Figure 5: Langelier-Ludwig diagram of some of the analyzed groundwater samples.

As concerns the secondary constituents, the thermal waters are marked by higher concentration of Li^{+}, Sr^{2+}, F^{-} and Br^{2+} respect to those measured for the cold-water samples. They are also characterised by relatively high Ca+Mg/Sr and Li/Cl ratios, as shown in Figures 6 and 7. Lithium is considered as a reliable indicator for the residence time of groundwater in the aquifer (Edmunds and Smedley, 2000).

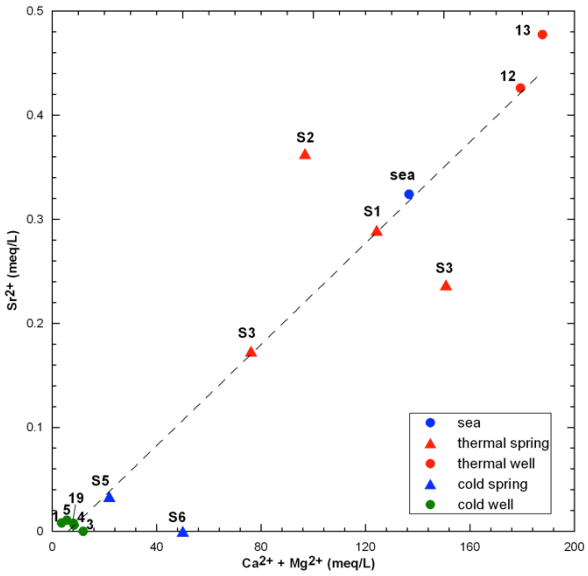

Figure 6: Sr^{2+}-Ca^{2+}+Mg^{2+} correlation plot for the water samples reported in the text.

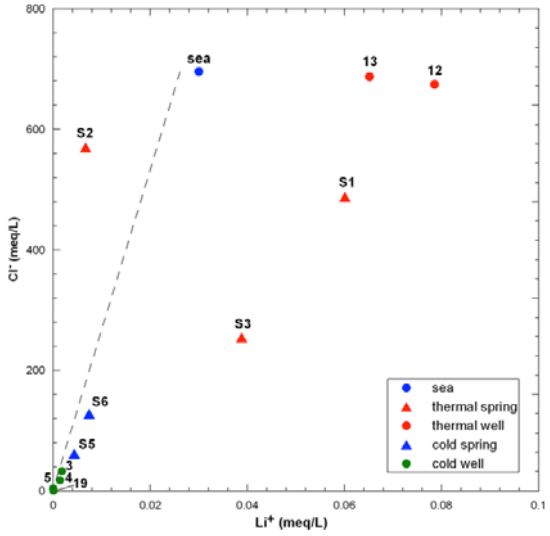

Figure 7: Li-Cl correlation plot for water samples reported in the text.

Most of the trace element concentrations are related to the redox environment of thermal waters. As a matter of fact, the measured redox potential values range from negative to slightly positive (-300 mV to 30 mV).

The D/H isotopic ratios have been plotted in a $\delta^{18}O$–δD diagram (Craig, 1963) shown in Figure 8 where the Global Meteoric Water Line (GMWL) and the Mediterranean Meteoric Water Line (MMWL; Gatt and Carmi, 1970) are also reported. As shown in

Figure 8, the cold water samples (1, 5, 4, 3, 19) fall between the two lines, thus suggesting a meteoric origin of the samples. The thermal waters sampled at both wells (12, 13, 14) and springs (S1, S2, S3, S4) plot to the right of both the water lines (Fig. 8), as the seawater sample, suggesting enrichment in oxygen $\delta^{18}O$. This shift could be interpreted as due to evaporation of deep fluids (Panichi, 1982).

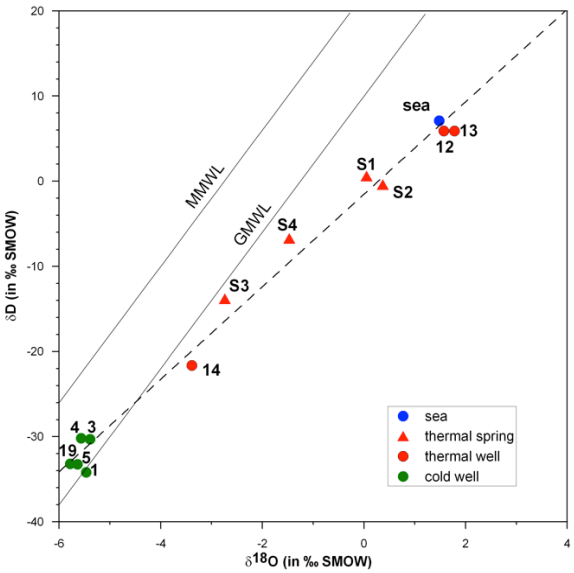

Figure 8: Binary δ D - δ 18O diagram for the water

The tritium content measured for some waters sampled in the studied zone is reported in Figure 9 together with the chloride amount obtained for the same samples. As resulted from the analyses carried out, the thermal waters sampled at the wells (12 and 13 in Fig. 9) record a low tritium content while higher contents, up to almost 5 TU, occur for the cold water samples. These results suggest that the thermal waters should be recharged by groundwater characterized by a relatively long residence time (greater than 55 years), connected to a deep groundwater circulation system. In addition, the data for the cold-water samples provide evidence of recent recharge.

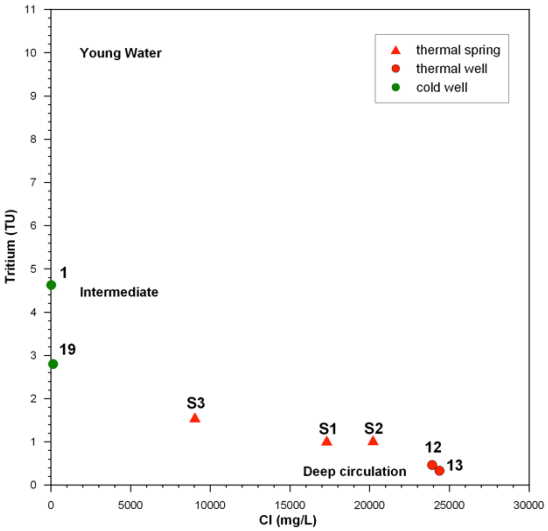

Figure 9: Tritium-Cl correlation plot.

As gathered from Figure 10, the thermal waters sampled at the wells are undersaturated with respect to calcite and dolomite, as resulted from the calculations of equilibrium of waters with these carbonates.

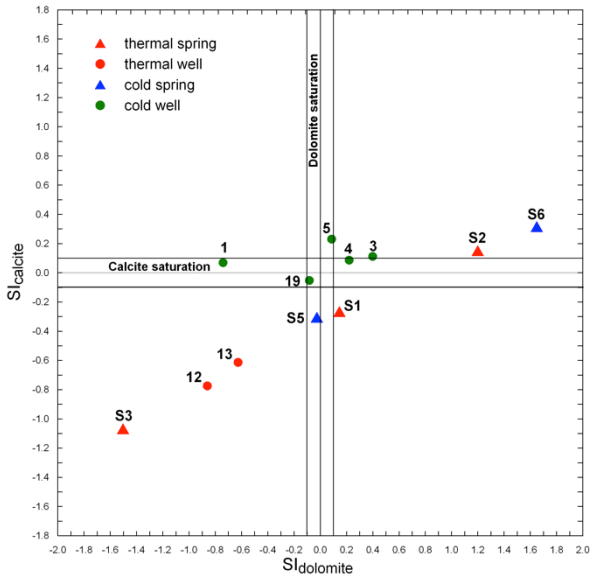

Figure 10: The saturation state of groundwater with respect to calcite and dolomite.

4. CONCLUSIONS

The thermal system of Santa Cesarea, which has been used for spa from several decades, seems essentially due to three water types or components: 1) pure fresh groundwater from meteoric infiltration in the carbonate rocks, 2) saline water due to seawater intrusion, 3) a thermal saline fluid rich in sulphur. The resulting mixture is undersaturated with respect to calcite, thus aggressive enough to enhance the karst processes in the area.

Moreover, due to both the geochemical composition and the physical features of the sampled waters, the thermal waters should be moving from ancient seawaters subjected to intense evaporation processes, infiltrated at great depth within the seabed substratum. Afterwards, these thermal fluids should flow up through the almost vertical structures, related to the transtensional structures, identified within a narrow sector of the studied territory.

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Acknowledgements

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