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Conceptual Modeling and Tracer Testing at Ribeira Grande, São Miguel, Azores, Portugal

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ABSTRACT

The Ribeira Grande geothermal reservoir on São Miguel Island, Azores, is exploited by two different production/injection areas on the northern side of the Lagoa do Fogo (Agua de Pau) volcano, both developed and operated by Sociedade Geotérmica dos Açores, S.A. (SOGEO). The southern (upslope) area has been in continuous production since 1994 and now has a 13 MW capacity. The northern (downslope) area has been in continuous production since 1981, with an expansion from 3 MW to 10 MW that went on-line in 2006. To support the expansion and plans for continued development in the northern area, the conceptual model of the reservoir has been updated, a tracer test conducted, and a numerical model developed. The reservoir is fed by a 240°C upflow of relatively alkaline, Na-Cl water that appears to occur in the southeastern quarter of the southern area. Outflow is to the north, and the reservoir as a whole is marked by a striking degree of chemical homogeneity and limited cooling along a horizontal distance of more than 3 km. The conceptual model is constrained somewhat by limited drilling (one well) in the gap between the southern and northern production areas. Tracer injected at the northern edge of the southern production field (one well) shows very limited returns to the south (0 ~ 3 ppb), and was not seen to the north (1.75 km and further) after 240 days. Tracer injected at the northern edge of the northern production field (two wells) shows more rapid and substantial returns (10 ~90 ppb) to wells of the northern field, and it is planned to relocate this injection further to the NE. Results of early exploration drilling, and locations of surface manifestations, indicate that an eastward and southeastward expansion of the northern production/injection area should be possible, whereas further expansion of the southern production area is limited by severe surface topography and limited access. SOGEO plans to conduct step-out drilling for production and injection both, in late 2009.

1. INTRODUCTION

Sociedade Geotérmica dos Açores (SOGEO) has requested that GeothermEx carry out an update of the conceptual and numerical model of the Ribeira Grande geothermal reservoir, located in the central part of the island of São Miguel (Figure 1). This paper presents the results of the tracer testing conducted in 2007-2008, and the conceptual model update.

2. CONCEPTUAL HYDROGEOLOGIC MODEL

2.1 Results of Recent Drilling

The Ribeira Grande geothermal field has been investigated by deep and shallow drilling, as well as by surface investigations (including geological, geochemical and geophysical surveys) during more than three decades since discovery wells were drilled in the early 1970s (Muecke and others, 1974) and late 1980s (Henneberger and Rosa Nunes, 1990). The results of these investigations have been used to interpret subsurface geology and geothermal reservoir conditions at various times during the course of the development of the field.

GeothermEx has developed and periodically updated a conceptual model of the Ribeira Grande system that incorporates geology, temperature and pressure conditions, and other reservoir characteristics. This model has been proposed in 1996, since then new information about subsurface conditions has become available, principally from the drilling of 6 new wells in the field (CL6, PV4, PV5, PV6, PV7, and PV8; locations are shown in Figure 2). For the most part, the results of the new wells confirmed the existing conceptual model; however, they also revealed or clarified several characteristics of the geothermal system that had not been known previously. The principal new results that have emerged from the recent drilling are as follows:

- Reservoir temperatures, and possibly reservoir permeability, appear to diminish to the south of the Cachaços-Lombadas area (i.e., to the south of wells CL2, CL3, and CL5) more abruptly than had been thought previously to be the case.

- The trend noted above, along with the slight temperature reversals observed in many of the Cachaços-Lombadas wells, implies that the principal zone of upflow for the geothermal system is not located toward the center of the Fogo volcano (with respect to the developed field), but rather at some unknown location to the east or northeast of the Cachaços-Lombadas wells (to the southeast of Mata do Botelho).

- A zone of high temperature and very high reservoir permeability is present in the zone immediately to the east and southeast of the cone of Pico Vermelho. This zone was revealed by the results of wells PV4 and PV8, and, to a lesser degree, PV7. This finding is particularly noteworthy because PV8 is essentially a replacement of well PV1, which nevertheless did not show similar temperature and permeability characteristics.

- Reservoir permeability in the northern part of the Pico Vermelho sector (in the vicinity of wells PV5 and PV6) is somewhat more limited than it was previously thought to be, particularly considering that corehole TG4 was reportedly productive despite its small diameter. The temperature profiles of wells PV5 and PV6 confirm that they are located inside the limits of the geothermal reservoir (as expected), but they initially had low flow capacities that needed to be increased by stimulation (through sustained injection) before they could be used as injection wells for the new Pico Vermelho power plant.

Aside from these new inferences, the conceptual model of the Ribeira Grande geothermal system has not changed significantly as a result of the new development and exploitation of the field in the past several years. It may be noted that the results of the tracer testing conducted during 2007-2008 have tended to confirm the overall model of the shape and extent of the geothermal reservoir; that is, in the Pico Vermelho sector the reservoir is confined to a relatively narrow vertical interval a few hundred meters thick, whereas in the Ribeira Grande (Cachaços-Lombadas) sector it is much thicker, and possibly more extensive laterally. As a result, much stronger tracer returns were observed from the Pico Vermelho injection wells PV5 and PV6 (at the Pico Vermelho producers) than from injection well CL4 (at the Ribeira Grande producers).

2.2 Temperature Distribution

The distribution of temperature in the Ribeira Grande geothermal system has been deduced from temperature profiles measured in the various deep wells drilled in the field. Stabilized formation temperatures have been interpreted from the measured profiles, taking into account and adjusting for the perturbations caused by wellbore effects such as boiling and circulation between different zones or around the production liners.

Temperature distribution is important to understanding and modeling the geothermal system, in part because it is a critical set of data against which to calibrate the initial-state numerical model of the system, and also because it provides a means of interpreting and understanding the patterns of fluid movement within the geothermal reservoir.

Near sea level (Figure 3), temperatures are distributed somewhat irregularly, with apparent "hot spots" located in the vicinity of wells PV8 and CL1. Wellbore effects make the interpretation of temperatures at this level somewhat less reliable than at deeper levels in the reservoir.

Figures 4 and 5 show the distribution of temperature from -200 m msl (mean sea level) to -400 m msl where the main production zones are located. The following important aspects of the temperature distribution can be observed in these figures:

- With increasing depth, the overall shape of the reservoir zone, which is elongated along a NW-trending axis, becomes more evident. By -200 msl, a zone of higher temperatures is present in the PV8-PV4-PV7 area. At -400 m, temperatures are nearly isothermal over a significant distance in the SE-NW direction, indicating strong lateral outflow to the NW at or near this level.

- At the -600 m msl level (Figure 6), the zone of high temperatures is seen to become more localized in the Cachaços-Lombadas area (with the highest observed temperatures generally present at wells CL3 and CL4). At deeper levels temperatures are decreasing with depth over most of the Pico Vermelho sector, indicating that the reservoir lies mainly above this level, whereas temperatures remain isothermal or continue to increase slightly in the Cachaços-Lombadas area.

- At the deepest levels drilled, the high-temperature zone is confined to the southern part of the field. There are not enough well data to determine the location of the principal upflow zone for the reservoir; however, the trends suggest that it may be located to the northeast of wells CL3 and CL4.

- The overall distribution of temperature is consistent with a single source of upflow, within or near the southeastern part of the field. The zone of higher temperatures observed at shallower levels in the PV8-PV4-PV7 area, which appears isolated in Figures 4 and 5, could be connected to the deeper upflow zone by upward and northwestward flow of deeper water.

- The limits of the geothermal reservoir have been only partly defined by deep drilling. There is significant evidence for the southern boundary of the field, and the southwestern boundary can be inferred with reasonable confidence from the temperatures observed in the Pico Vermelho wells, and the relatively cold and non-productive well SB1. To the east and northeast, however, the reservoir is not well delineated. Further drilling will be needed to determine conclusively the limits of the reservoir in these parts of the field.

2.3 Fluid Chemistry

Previous studies of fluids chemistry at the Ribeira Grande and Pico Vermelho geothermal wells have noted two fundamental characteristics that are significant with respect to the conceptual model and to effects of production on the reservoir.

First, the reservoir contains a Na-Cl (sodium-chloride) water with somewhat high HCO_3 (measured as alkalinity in samples collected), and well-to-well differences in chemistry are relatively small: i.e. the reservoir is relatively homogeneous, which suggests good and well-distributed permeability. Reservoir Cl is typically about 1,500-1,600 mg/l (locally higher) and HCO_3 is about 500 mg/l. The alkalinity level results in very low Ca (calcium) due to the low solubility of calcite ($CaCO_3$) at high temperatures. The source of the high HCO_3 is probably abundant CO_2 that enters the system from below: a large cold spring that releases CO_2 gas is located only a few km outside of the geothermal system to the east.

Second, because air-cooled binary power production is used in both sectors of the field, the spent geothermal water that is injected back into the reservoir is nearly identical in composition to the water produced.

Furthermore, the amount of historic pressure draw-down in the reservoir has been relatively small, which lowers any expectation that the reservoir would be affected by intrusion of sea-water from the north, or by down-flow of dilute meteoric water (probably with high HCO_3 relative to Cl) from above.

Therefore, Ribeira Grande is a geothermal field in which large shifts of chemistry as a result of exploitation are generally not expected to be seen. These characteristics and expectations are born out by the fluids chemistry data that are available from the production and injection wells and so-far include the new Pico Vermelho (PV) sector, even though only a few samples have been collected in that area.

2.4 Previous Tracer Test in the Ribeira Grande Geothermal Field

During 1998 a tracer test using uranine (fluorescein) dye was conducted in the Ribeira Grande Geothermal Field (Granados and others, 2000). The tracer was injected into injection well CL4 and over a period of approximately two months, water samples from the production wells CL1, Cl2, CL3, and PV1 were collected and analyzed using a laboratory filter fluorometer. The results revealed no detectable return of tracer in any of the production wells.

2.5 Choosing the Type of Tracer

After researching tracer tests developed in several geothermal fields worldwide, SOGEO, with assistance from GeothermEx, designed and contracted services for conducting a tracer test at the Ribeira Grande Geothermal Field using naphthalene disulfonate (NDS) tracers. This particular type of tracer was chosen largely because of the advantages presented: NDS isomers are thermally stable in high temperature reservoirs (thus are long-lived); there is none of this type of chemical naturally present in the reservoir; multiple NDS isomers could be detected in a simple sample, which allows testing two or more wells at the same time; and the chemical compound is environmentally benign and non-toxic.

From the group of naphthalene disulfonic acid tracers studied in the laboratory and in the field, the 2,6-NDS, 2,7-NDS and 1,6-NDS tracers were chosen for having better detection limits and for having quick elution times. Of the three tracers, the 2,6-NDS and 2,7-NDS seem to decay more slowly than the 1,6-NDS, when compared over a period of years, according to some authors.

Considering the location of the three injection wells within Ribeira Grande Geothermal Field, one of the "2" series tracers were determined to be more adequate for wells CL4 and PV5, and the 1,6-NDS more suited for well PV6.

2.6 Tracer Test Operations

Before the beginning of the tracer test, all geothermal wells were sampled by collecting samples of water (brine) separated from steam, in order to control any tracer baseline contamination. Samples of each raw tracer, and from each tracer solution (10%), were also collected. Brine samples were collected into 100 ml clear plastic HDPE bottles, using separate stainless steel cooling coils in order to avoid cross contamination of samples.

On October 10, 2007, 100 kg of 1,6-NDS was dissolved in $1m^3$ of fresh water and injected into injection well PV6, through a flexible flow line that connected the tracer tank to wellhead wing valve, which took about 7 minutes. In the same day, a 10% solution of 2,6-NDS and of 2,7-NDS were also prepared and injected into injection wells PV5 and CL4, respectively. The 2,6-NDS solution was injected at a rate of approximately 2.8 l/s and the 2,7-NDS solution at 1.7 l/s. All tracer solutions were sucked into the wellhead, which was on vacuum. The amount of tracer determined for injection was based on the estimated reservoir volume and porosity.

2.7 Tracer Test of 2007-2008

The test comprised injecting 100 kg of three different isomers of naphthalene di-sulfonic acid into three different injection wells, CL4, PV5, and PV6. Production wells monitored over a period of 33 weeks were: CL1, CL2, CL5, CL6, PV2, PV3, and PV4. Injection water at CL4 and PV6 (same as injection to PV5) was also sampled routinely. Initial sampling frequency was high and as the test progressed it was reduced as follows:

Weeks 1 and 2:	2 samples per well per day
Weeks 3 and 4:	1 samples per well per day
Weeks 5 to 8:	3 samples per well per week
Weeks 9 to 16:	2 samples per well per week
Weeks 17 to 33:	1 sample per well per week

Analyses of the samples collected at production wells were done at the Energy and Geoscience Institute (EGI) at the University of Utah, Salt Lake City, Utah, U.S.A., using High Performance Liquid Chromatography (HPLC). Samples were analyzed in batches collected at ~30 day intervals, to allow vetting early results for errors and trends. After some problems with contamination or other interferences in the samples collected on the first few days, which were successfully overcome, all analyses proceeded smoothly and the results (summarized on Figures 7 and 8) are considered to be quite good.

There was very little return of the tracer injected to well CL4, and this appeared only at well CL5 (never above ~4 ppb) and, after 186 days, at CL6 in very small amounts. In contrast, tracer injected to PV6 returned to PV-sector production wells at levels as high as 88 ppb, and tracer injected to PV5 returned to PV-sector production wells at levels as high as 20 ppb.

It appears that a strong hydraulic connection exists between production well PV2 and injection well PV6. Figure 7 shows that the 1,6 NDS tracer came back to production well PV2 in 12 days, and the peak amount was about 87 parts-per-billion (ppb) at day 56. This rapid and strong return of the injected tracer suggests that these two wells are strongly connected, which may result in significant thermal degradation of the produced fluid temperature from this well in the future if injection is continued at PV6. Note that, at about day 110, the slope of the measured tracer return curve changes: instead of continuing with a "bell" shape, the shape of the tracer return curve broadens out. This is due to the secondary return of tracer that has been produced at the production wells and then reinjected back into the reservoir.

Figure 7 also shows the 1,6 NDS tracer returns obtained for well PV3. Although PV3 is located much closer to PV6 than PV2, the degree of tracer return is smaller (45 ppb compared to 87 ppb), and the tracer first appeared at PV3 on day 15 (3 days later than at PV2), suggesting that the hydraulic connection between PV3 and PV6 is less direct than the connection between PV2 and PV6. Still, the relatively large amount (45 ppb), and fast arrival time (15 days) signal a strong likelihood of long-term thermal degradation potential at this well if injection is continued at PV6.

The measured 1,6 NDS tracer returns for well PV4 is also shown on Figure 7. With a strong tracer return (41 ppb) and a fast first-arrival time of 9 days, it is clear that there is a strong hydraulic connection between injection well PV6 and production well PV4. Although PV4 is located about 1.3 km away from PV6, this strong connection would likely cause thermal degradation in well PV4 in the future if injection is continued at PV6. It is anticipated that cooling would also occur at PV8 (which was not sampled), as it is located between PV4 and PV6.

For the 2,6 NDS tracer injected into well PV5, a significant amount of tracer return was detected at PV4 (Figure 7). A maximum concentration of 20 ppb was detected at well PV4 on day 124, with a first-arrival time of 40 days, suggesting a relatively strong connection between PV4 and PV5. Long-term injection at PV5 could potentially cause thermal degradation at wells PV4 and PV8.

A weaker hydraulic connection exists between PV2 and PV5, as shown on the same figure. The measured 2,6 NDS tracer return did not appear at PV2 for 56 days, and its return maximum magnitude is about 9 ppb. A similar magnitude of the tracer return is also detected at PV3. The peak amount is about 10 ppb on day 160, with the first tracer arrival on day 56.

The 2,7 NDS tracer injected into CL4 was not detected at well PV2 during the sampling period (Figure 8). This is expected, as CL4 is far away from the Pico Vermelho production zone, and it suggests that injection at CL4 would probably not cause any negative impact on the thermal characteristics of well PV2.

No 2,7 NDS tracer injected into CL4 was detected at PV3 during the sampling interval (Figure 8). This does not suggest that there is no hydraulic connection between the two wells; rather, the distance between the wells is too great, and therefore the injected tracer spreads out and becomes undetectable. The conclusion from this is that injection at CL4 should not result in any thermal degradation in the fluid temperature produced at PV3.

Tracer 2,7 NDS injected into CL4 was not detected at well PV4 during the sampling duration, suggesting injection into the Ribeira Grande area at the current rate would not cause thermal degradation at downstream Pico Vermelho wells.

No tracer injected into the Pico Vermelho injection wells (PV5 and PV6) was detected at any of the Ribeira Grande production wells. A small amount of the 2,7 NDS tracer injected into CL4 was detected and matched by the model at CL5, as shown on Figure 8. Although the 2,7 NDS tracer arrived at CL5 relatively quickly (first-arrival time of 22 days), the small amount (~4 ppb) of tracer return suggests a minimal impact of injection at CL4 on the production characteristics of CL5.

The other Ribeira Grande production well that has seen tracer return was CL6; this return was detected in the last batch of tracer data collected (sent on June 16). A minute amount (0.4 ppb) of the 2,7 NDS tracer was detected at CL6 on day 183. Again, the weak return and long arrival time suggest that injection at CL4 should not cause any detrimental impacts on the thermal characteristics of the Ribeira Grande production wells.

These tracer returns have been modeled using numerical simulation, as described in Pham et. al., (GRC 2009).

3. CONCLUSION

The Ribeira Grande geothermal field is an extensive, high-temperature geothermal system hosted by volcanic rocks (mainly lavas and pyroclastic units) on the northern flank of the Fogo volcano. The geothermal reservoir is elongated in a northwestern direction, and may have southwestern and northwestern boundaries that follow this trend, particularly at lower elevations. However, the field is insufficiently delineated by drilling to be certain of its limits, and recent geoelectrical surveys suggest a possibility that the field extends further to the northeast than was thought previously to be the case.

Thermal water with a maximum temperature of at least 250°C enters the reservoir in an upflow zone that is probably located in the southeastern part of the field (to the east of the Cachaços-Lombadas wells). The ultimate source of heat for the thermal water is presumably the body of magma or young intrusive rock associated with the activity of the Fogo volcano.

The principal flow direction into and within the reservoir at deeper levels is upward and northwestward, though there is probably some lateral flow toward the margins of the reservoir as well. The available data do not strongly indicate the presence of more than one upflow zone, but they do not preclude it either. At shallower levels (particularly near about -400 m elevation), lateral, northwestward flow appears to predominate over upward flow, forming an extensive, relatively shallow reservoir in the Pico Vermelho sector.

The reservoir fluid is a Na-Cl water with somewhat high HCO_3, and appears to be fairly homogeneous in composition throughout the field. Reservoir Cl is typically 1,500 to 1,600 mg/l, though it is locally higher. Although the reservoir contains predominantly liquid water, boiling occurs and forms a steam or two-phase zone at the top of the reservoir in some sectors of the field (this is evident in both temperature profiles and production enthalpies of certain wells).

The results from the 2007-2008 tracer test program suggest that the rapid and relatively large-magnitude return of the tracer injected into well PV6 to wells PV2, PV3 and PV4 indicates that PV6 injection can be expected to have a detrimental effect on the fluid production temperature of these producers at some point. It may also be anticipated that PV8 will also eventually be negatively impacted by the injection into PV6, because this well is close to PV2 and PV4. Injection into PV5 may also negatively impact the temperature of the produced fluid of the Pico Vermelho wells, but to a lesser degree than PV6. Very little of the tracer injected into CL4 was found in the Ribeira Grande production wells, suggesting that injection into CL4 should not have a significant negative impact on the wells' thermal characteristics.

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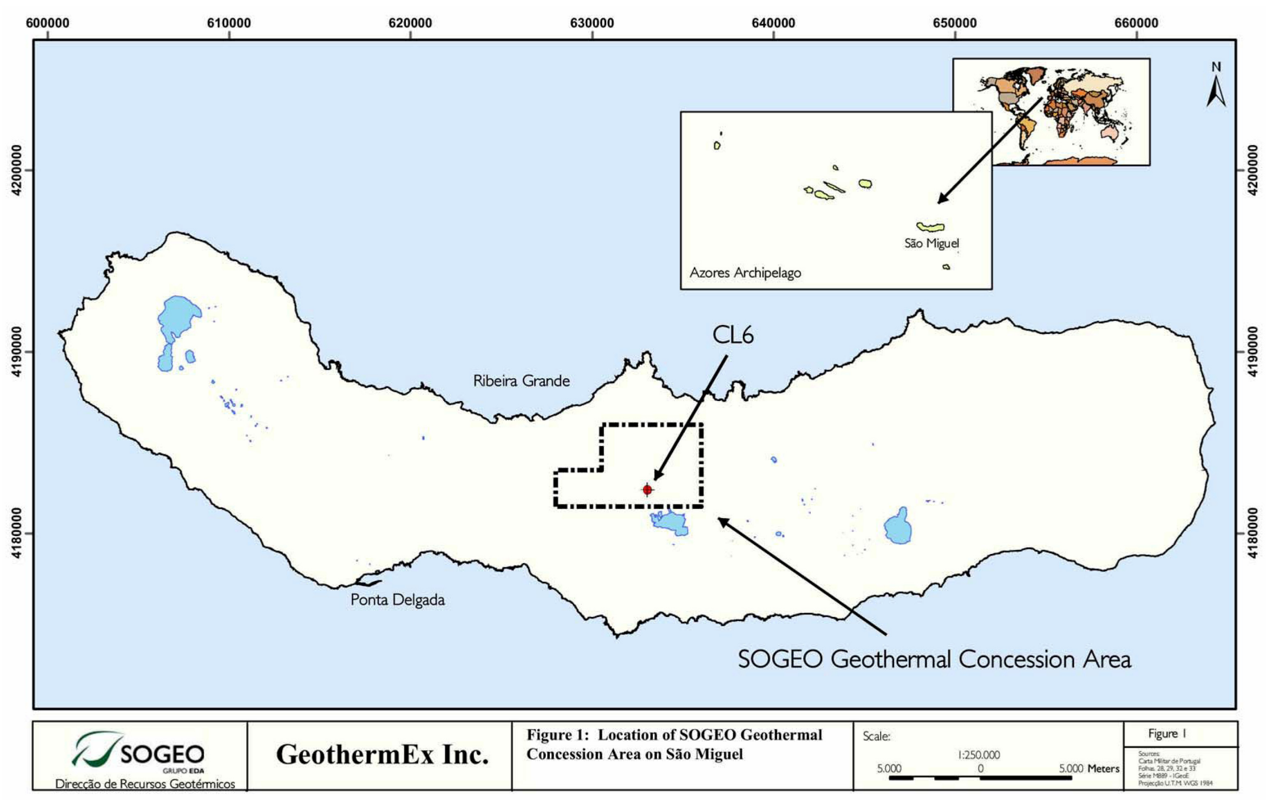

Figure 1: Location of SOGEO Geothermal Concessions Area on São Miguel.

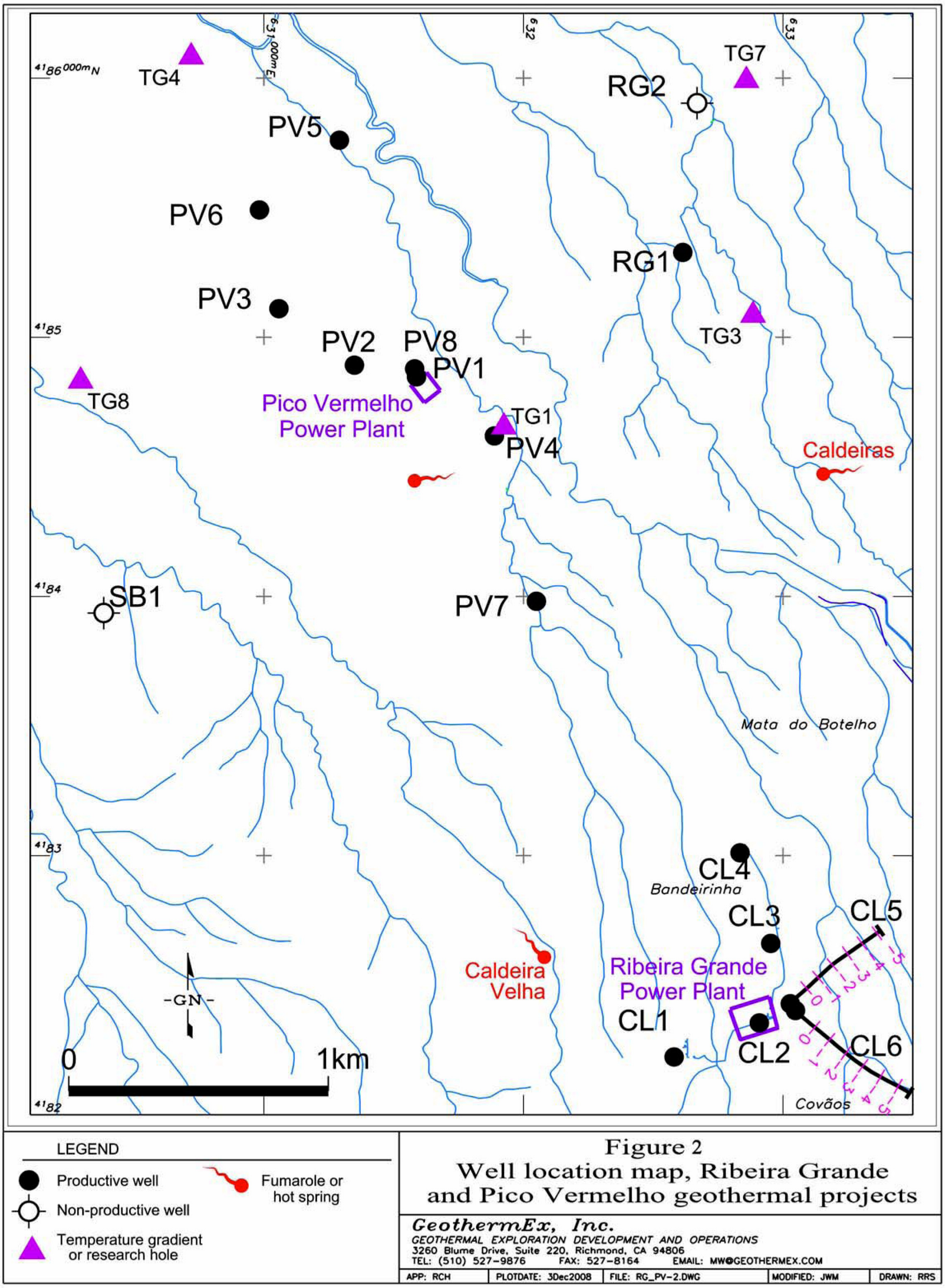

Figure 2: Well location map, Ribeira Grande and Pico Vermelho geothermal projects.

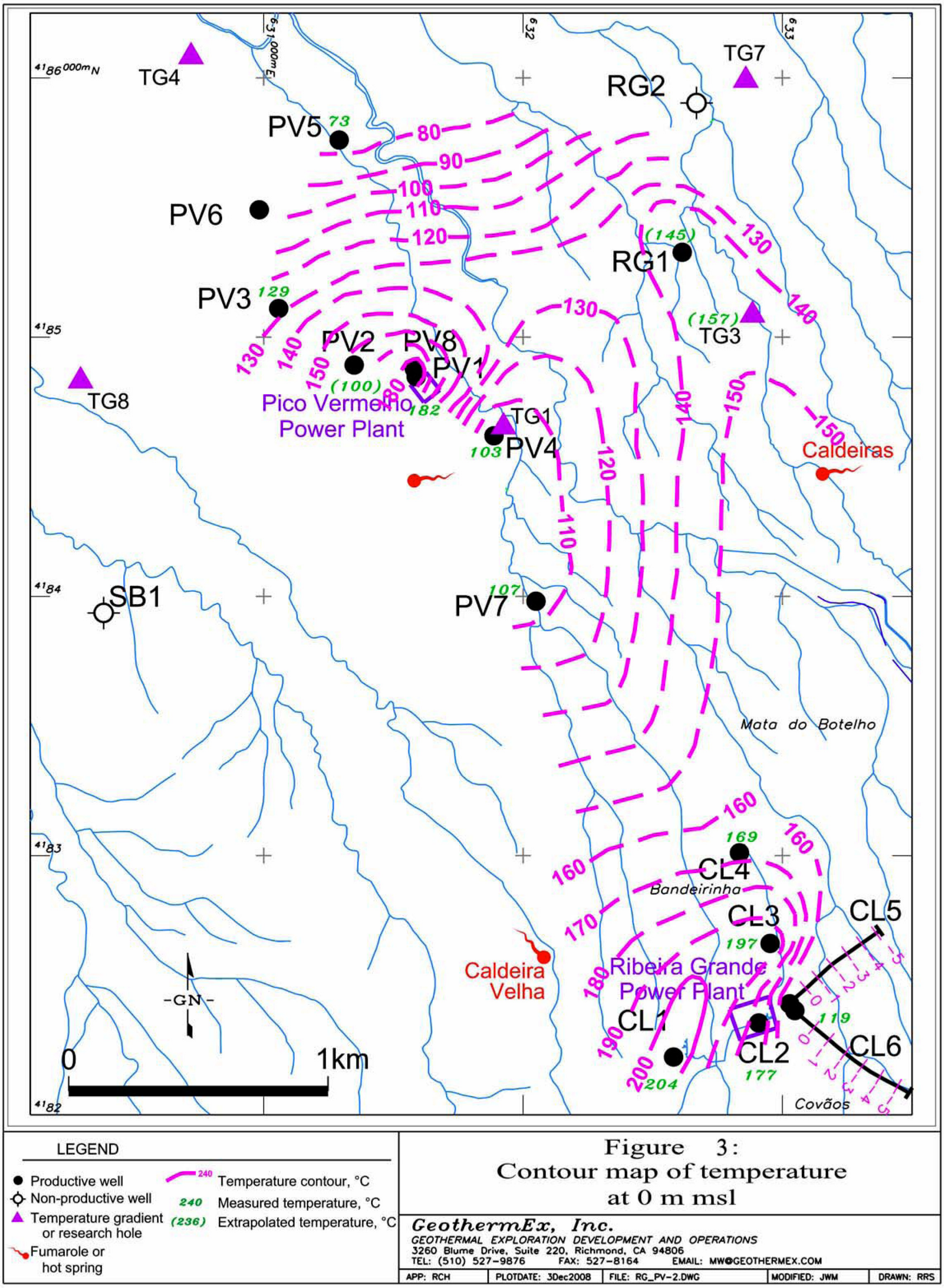

Figure 3: Contour map of temperature at 0 m msl.

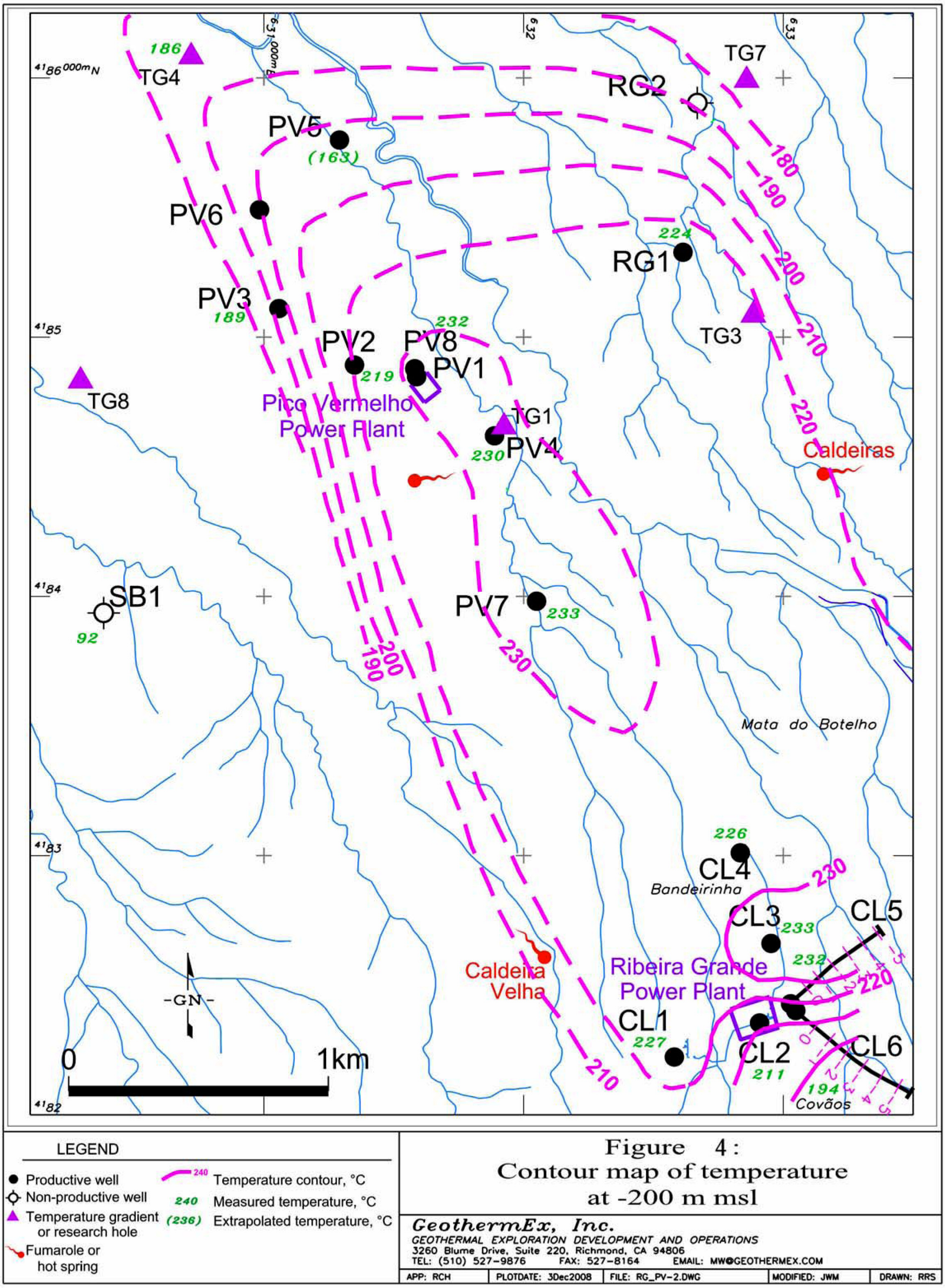

Figure 4: Contour map of temperature at -200 m msl.

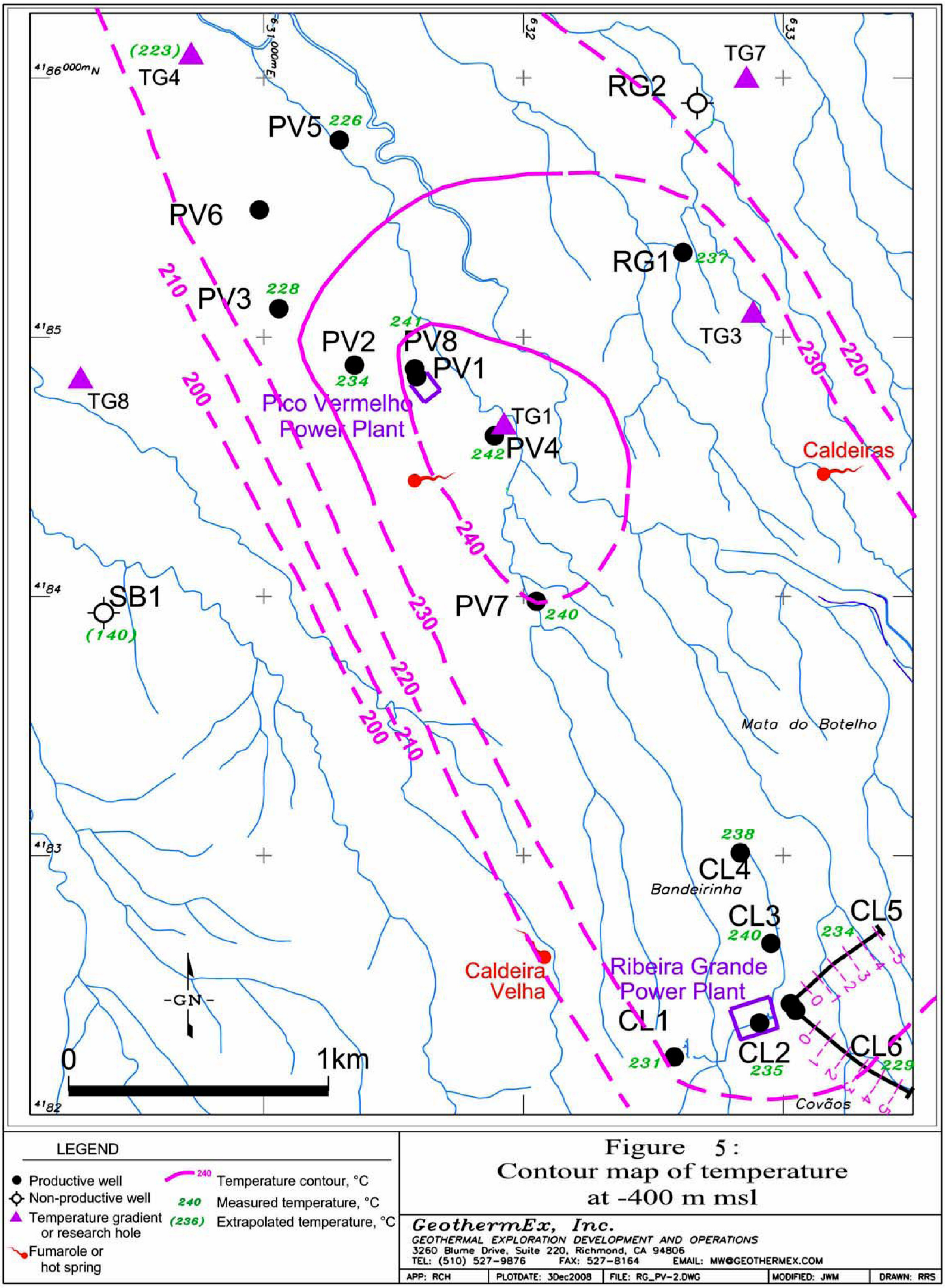

Figure 5: Contour map of temperature at -400 m msl.

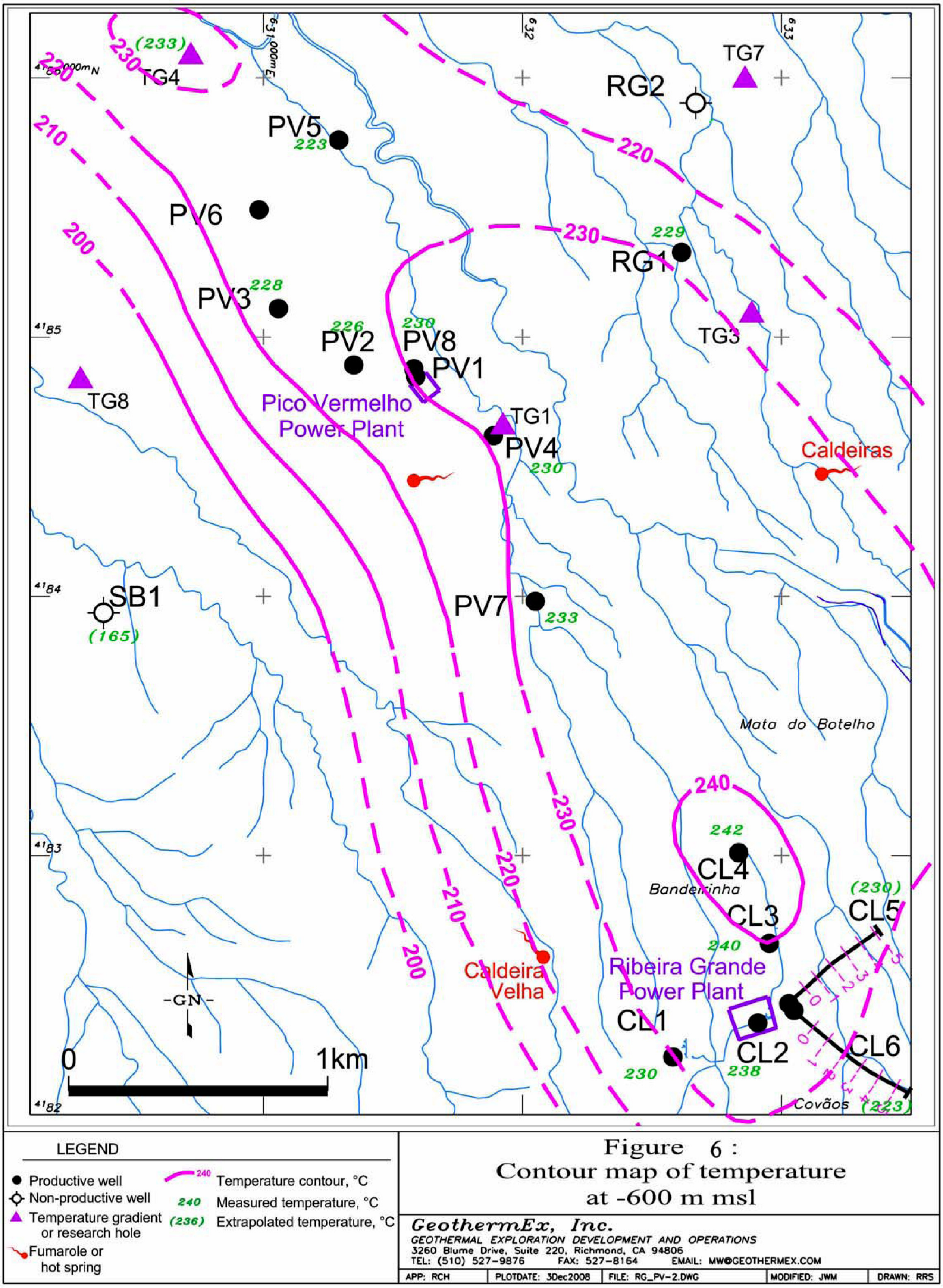

Figure 6: Contour map of temperature at -600 m msl.

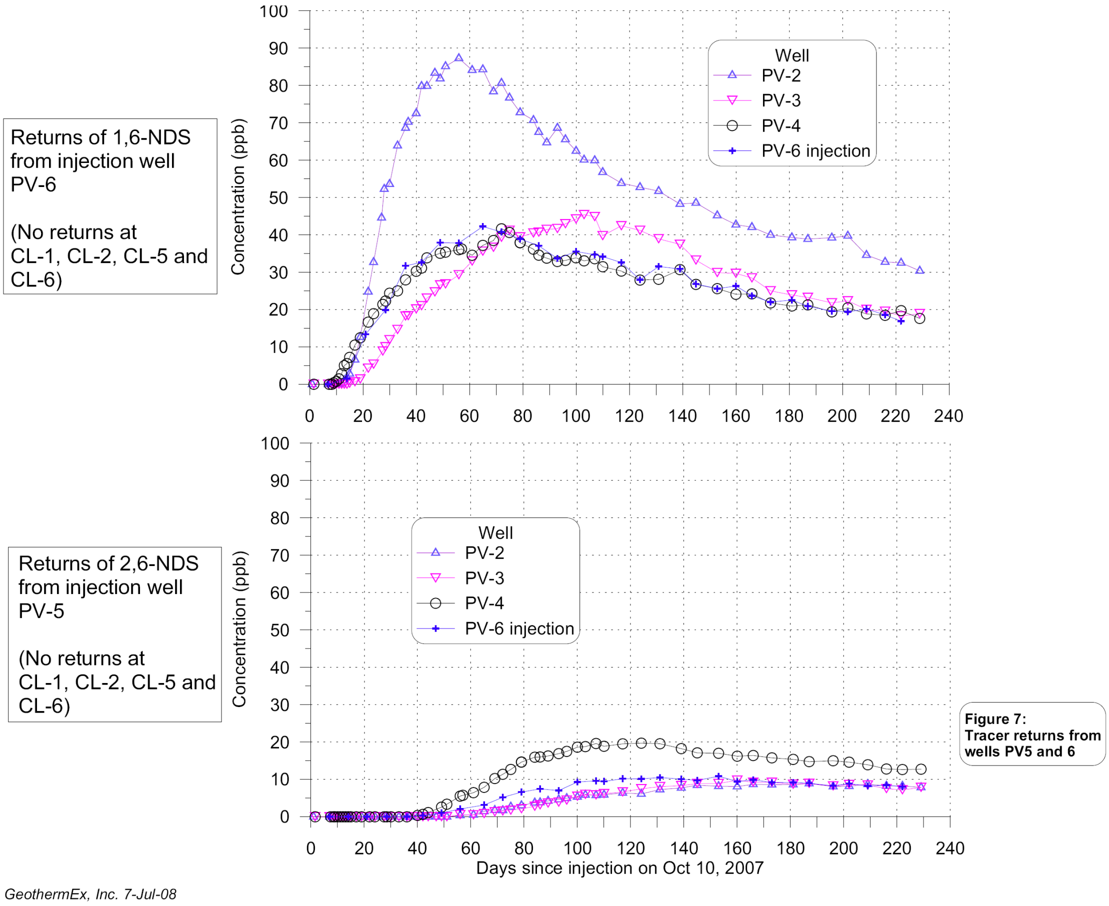

Figure 7: Tracer returns from wells PV5 and PV6.

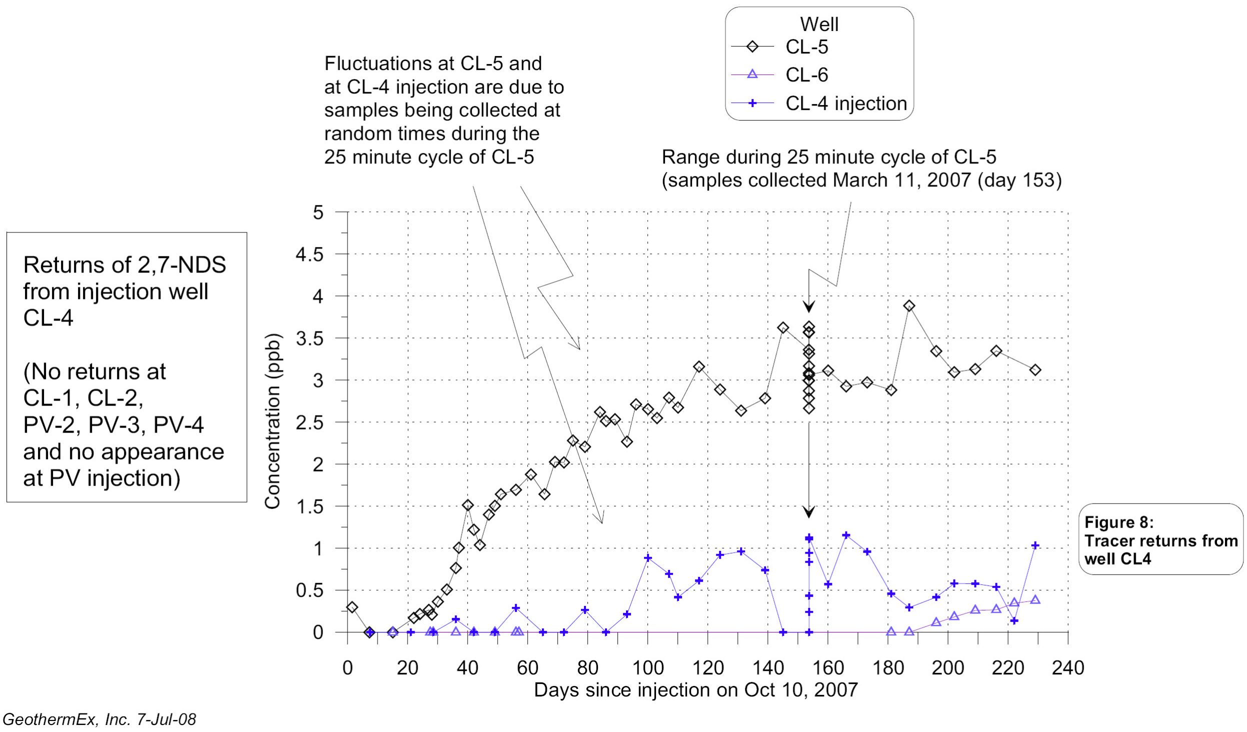

Figure 8: Tracer returns from well CL4.