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Landsvirkjun

Þeistareykir

Revision of the Geological and Alteration Model

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Title: Þeistareykir - Revision of the Geological and Alteration Model.

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Abstract: In 2016 and 2017, nine production wells were drilled in Þeistareykir. While drilling these wells, information on the geothermal system was collected, for example geological and geophysical data. Two geological models were generated, one small and one large. Lithological correlation was conducted using cutting analysis and well logs from the production wells. Seven faults cross the production area and they are mainly based on surface mapping. In this revised geological model, the dip of two faults was changed to more vertical. A discrete log was prepared for the model, where felsic/intermediate formations were analyzed or described in well reports and where gamma ray showed high anomaly, possibly reflecting felsic or intermediate formations. Seven felsic/intermediate formations were detected in the Þeistareykir wells.

The overpressurized zones in the wells on pads A and C were usually described the same, as a precipitation rich tuff or breccia. Calcite and pyrite rich and soft. It is very likely that the high pressure is therefore following this permeable formation.

Several alteration models have been generated using various alteration information from the Þeistareykir wells, for example from cutting analysis, XRD clay analysis and thin section analysis. In four wells, MLC and smectite appear deep in the well, after the occurrence of chlorite. This could be an indicator of cooling in the system and therefore could have impact on further development of the geothermal field.

Keywords:
Þeistareykir, Petrel, geological model, alteration, feed zones

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Approved by Landsvirkjun's project manager

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Ragnheiður Á.	Bjarni Richter

Table of contents

List of tables

List of figures

1 Introduction

Þeistareykir geothermal field in north of Iceland is considered to be one of the three largest geothermal areas in NE Iceland (Karlsdóttir et al., 2016). The geothermal system is a result of an active volcano and fissure swarm reaching the area from Mývatn (Sæmundsson et al., 2012). In 2002, the first production well was drilled but exploration in the area had been going on since 1972 (Karl Grönvold and Ragna Karlsdóttir, 1975). Most of the geothermal area is located below mt. Bæjarfjall and mt. Ketilfjall, which coincides well with were most of the surface manifestations are found (Figure 1).

In 2016 and 2017, nine production wells (ÞG-10 to ÞG-18) were drilled in Þeistareykir. While drilling these wells, information on the geothermal system was collected, such as geological and geophysical data. The geological data consists mostly of information from the drill cuttings such as lithology, stratigraphy and hydrothermal alteration and the geophysical data consisted of downhole logs such as temperature, pressure, natural gamma, resistivity, self-potential, neutron—neutron etc.

The aim of this project was to improve and update the geological and alteration models made in the Petrel software platform and update and revise the models to strengthen the conceptual model of the Þeistareykir geothermal field. Modeling was done using the Petrel software platform.

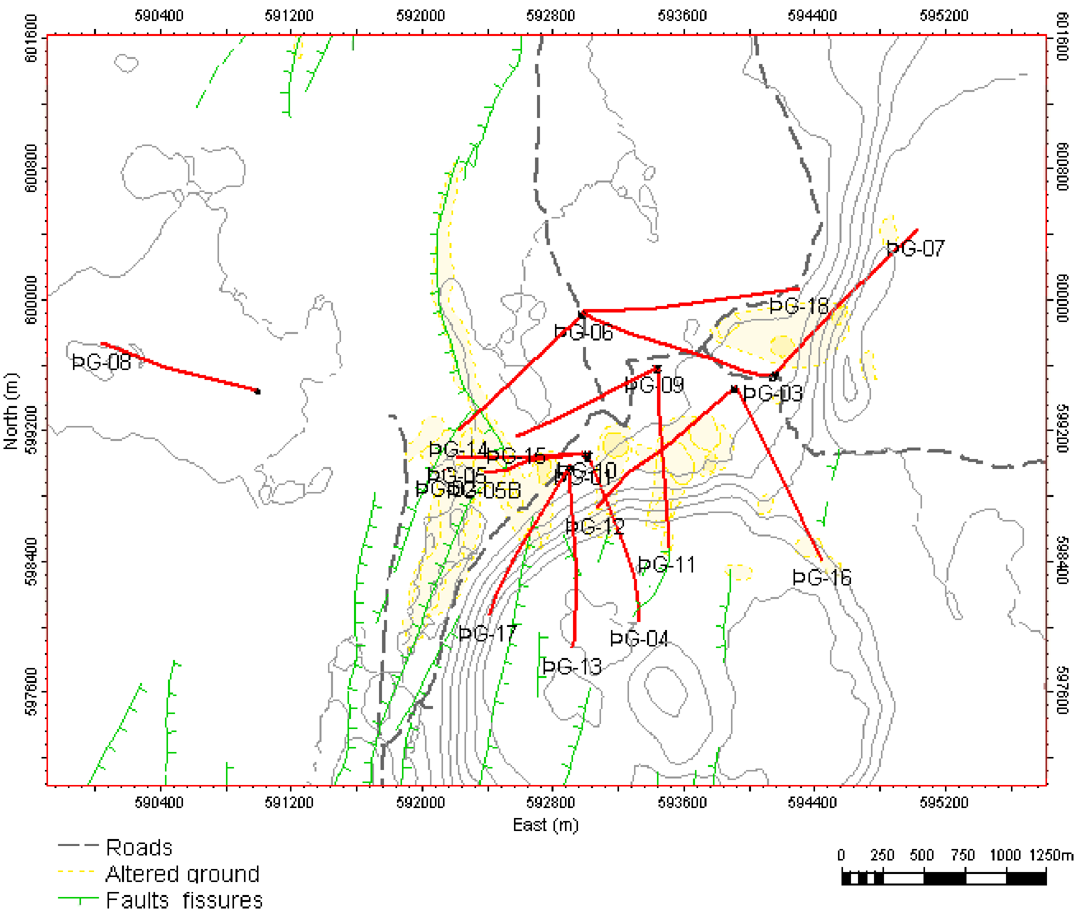

Figure 1. *Location of the Þeistareykir production wells, surface manifestations, surface faults and fissures and roads in the area.*

2 Imported data

A revision of the alteration and geological model was performed using data that has been gathered for wells ÞG-7 to ÞG-18, including:

- Geology
  - Cutting analysis; lithology, and intrusions
- Well logs
  - Caliper (X, Y arm)
  - Resistivity (16", 64")
  - Gamma ray and calculated SiO2 values
  - Neutron-neutron response cont.
  - Self-potential (SP)
- Hydrothermal alteration minerals
  - First occurrences of quartz, wairakite, epidote, prehnite, wollastonite, amphibole and maximum depth of calcite, based on binocular stereoscope analysis.
  - First occurrences of quartz, clorite, prehnite, epidote, wollastonite, amphibole and calcite disappears, based on thin section analysis using microscope.
  - Alteration zonation based on XRD analysis
  - Relative quantity of vein fillings, oxidation, pyrite and calcite
- Drilling data
  - Rate of penetration (ROP)
  - Weight on bit (WOB)
  - Circulation loss
- Feed zones
  - Relative sizes determined at the end of drilling
  - Active feed zones based on spinner measurements
  - Location of over-pressurized feed zones detected on well-pads A and C.
- Televiewer
  - Strike, dip, apertures and quality estimates of fractures added to wells ÞG-11 and ÞG-13.

3 Geological model

Two geological models were generated;

1) Smaller model, covering approximately 40 square kilometers around the Þeistareykir production wells where data density is relatively high and faults are included.
2) Larger model, covering approximately 400 square kilometers and represents the lithological units on a large scale. Faults are not included to this model. Figure 2 shows the areal extent of the two models.

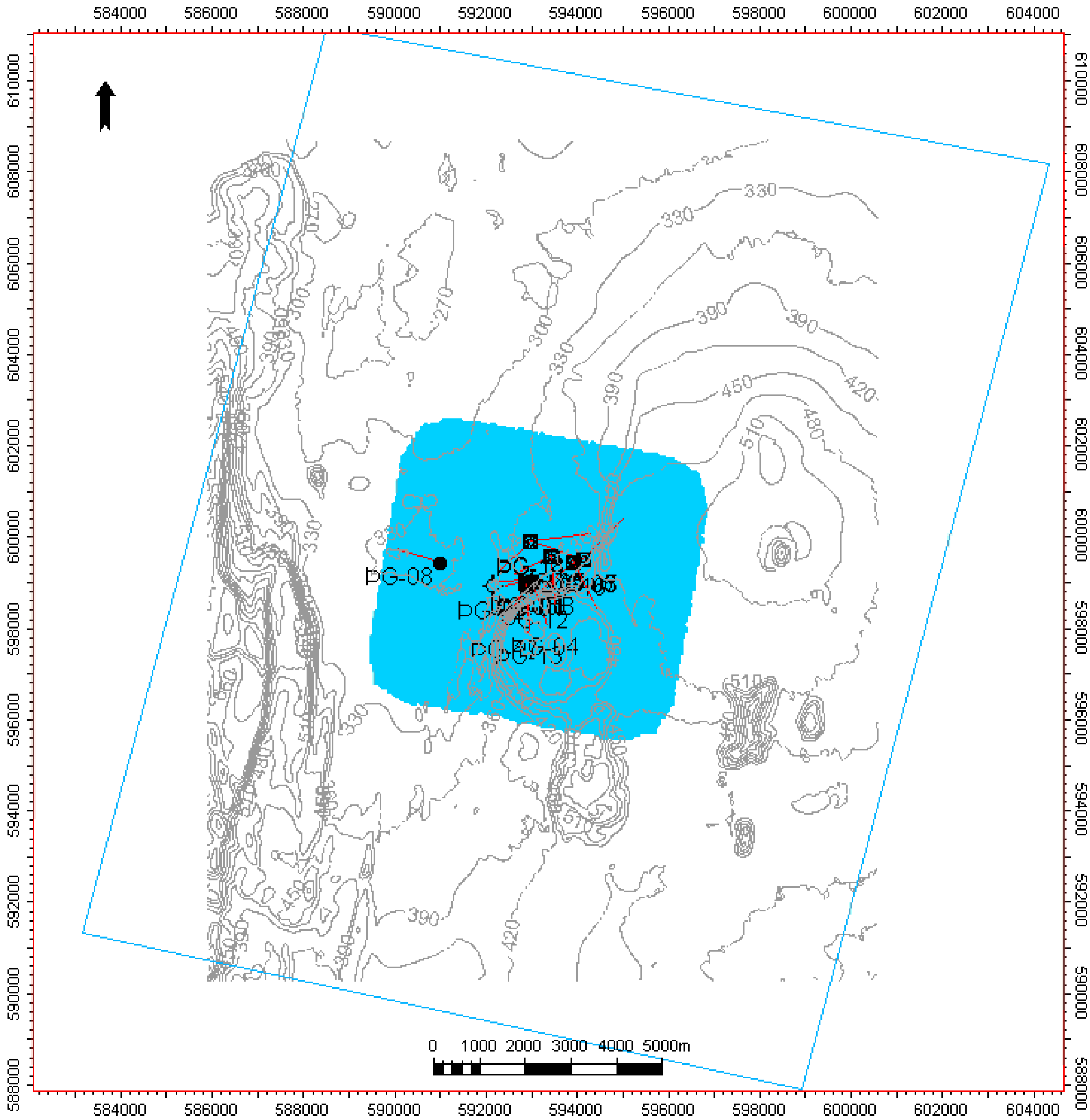

Figure 2. *The areal extent of the two geological models.*

3.1 Lithological units

Lithological correlation was conducted using cutting analysis and well logs from the production wells.

The most prominent units that were seen throughout the area are basaltic lavas in the uppermost 20–100 m, underlain by 80–100 m thick hyaloclastites where the formation become more tuff-rich in the lower part. From ~150 m a.sl to 800 m b.sl. the stratigraphy is composed of mixed hyaloclastites with thin layers of basaltic lavas. Below 800 m b.sl. the stratigraphy is mainly composed of basaltic lavas, with lenses of breccias and glassy basalt. The resulting model is composed of seventeen lithological units that were based on earlier observations from wells ÞG-1 to ÞG-6 (Table 1) (Mortensen, unpublished).

It was decided to exclude the andesitic lavas and rhyolitic tuffs from the earlier model, as these units were only observed in one well. Felsic units are discussed exclusively in chapter 3.3. Color legend for the different lithological formations and units are shown in Figure 3.

Figure 4 (to the left) shows a E-W section of the resulting geological model. The formations show a subsidence towards the west and a limited areal extent. The right figure displays a N-S section of the model, parallel to the rifting, showing less vertical displacement.

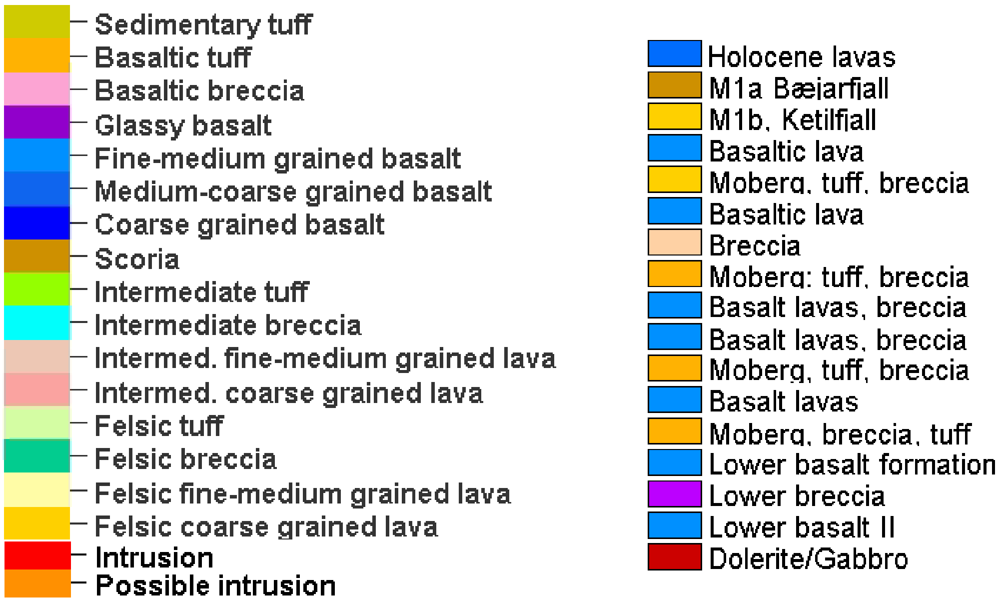

Figure 3. *Color legend for lithological logs (to the left) and for the geological model (to the right).*

Table 1. *Lithological units in the geological model of Þeistareykir. Modified from Mortensen (unpublished).*

Formation	Description	Max thickness (m)
Holocene lavas		
M1a Bæjarfjall	Tuff and breccia.	110
M1b Ketilfjall	Basaltic tuff and glassy basalt. Mixed with breccia. Contains plagioclas. Sedimentary tuff more prevalent towards west.	70-80
B2 Basaltic lava	Fine to medium grained basalt. Plag porphyric. Light green/grey. Changes in thickness represents a shield volcano.	30-120
M2, Moberg: tuff, breccia	Tuff, glassy basalt and sedimentary tuff. White and light green.	40
B3 Basalt lava	Basaltic breccia and basaltic lava. Plag porphyritic. Altered green.	20-30
M2b, Breccia	Basalt breccia and basalt lava. Oxidation in some samples.	50-100
M2c, Moberg: tuff, breccia	Hyaloclastite, tuff, breccia and basalt. Light green and gray. Aphyric. Becomes thinner towards east and west.	210
B4, Basalt lavas, breccia	Fine to medium grained basalt and glassy basalt and breccia. Light green and aphyric in some wells. Thickest in the western and central part.	30-130
B5, Basalt lavas, breccia	Medium to coarse grained basalt. Less altered.	
M3, Moberg: tuff, breccia	Breccias in the western part, breccia and tuff in east and south. Aphyric and altered. Breccias in the western part, breccia and tuff in east and south.	210
B6, Basalt lavas	Basaltic fine to medium grained lavas. Green/gray colored.	
M4, Moberg: breccia, tuff	Breccia, tuff and glassy to fine to medium grained basalt. Plag porphyritic. Breccia to the west and tuff to the east.	300-600
LB1, Lower basalt formation	Glassy to f/m basalt and breccia. Aphyric or sparsely plagioclas porphyritic. Marker horizon-increase in resistivity and NN.	
Lbr, Lower breccia	Altered breccia and tuff. Dark to light green. Resistivity shows a conductive layer	
Lb2, Lower basalt II	Fine to medium grained basalt and medium to coarse grained basalt. Feldspar porphyritic to non-porphyritic. Increase in resistivity and NN.	
Dolerite/Gabbro	Highly intrusive. Increase in resistivity and NN.	

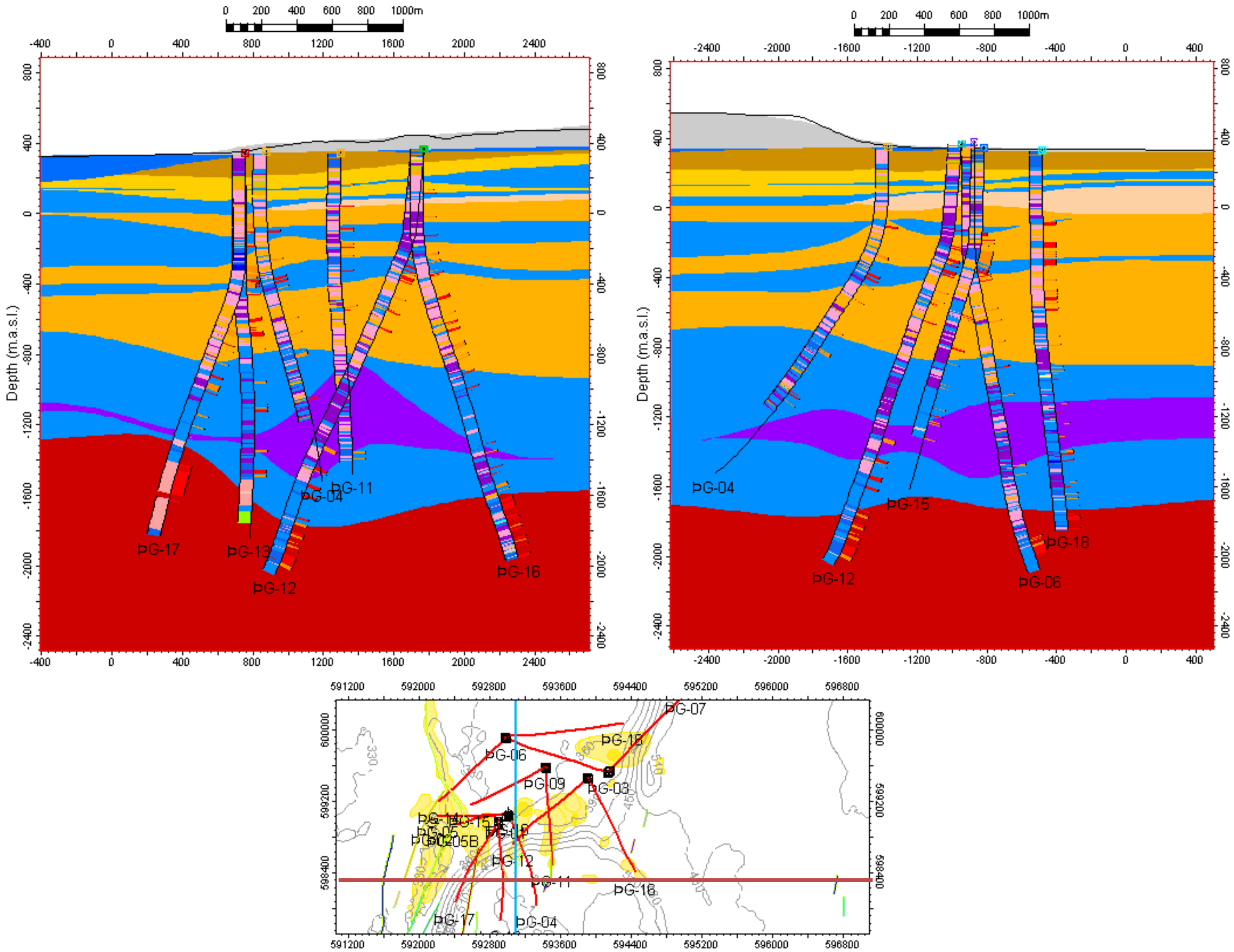

Figure 4. *A cross section showing the units of the geological model. The left section strikes E-W (orange line on map) and the right section strikes N-S (blue line on map). Lithology logs and intrusion logs are shown on the sections (see color legend in Figure 3).*

3.2 Faults and feed zones

Surface faults and fissures that had been imported to the previous model were included to the Þeistareykir geological model. Seven faults cross the production area and are likely to affect the structural pattern of the smaller geological model (Figure 5). They are mainly based on surface mapping, but in the revised geological model, their dip and dip direction were also supported by following datasets:

- Relative sizes of feed zones; available for wells ÞG-1 to ÞG-18.
- Active feed zones, based on spinner logging; available for wells ÞG-11 to ÞG-17.
- Borehole televiewer data; available for wells ÞG-8, ÞG-11, ÞG-13, ÞG-14 and ÞG-15.

A comparison between surface faults/fissures and additional structural borehole information (feed zones and televiewer data) revealed different dip of two faults; Þeistareykir 1 and Þeistareykir 2 (Figure 6). In the previous geological model (based on information from ÞG-1 to ÞG-6), their dip direction was towards SE. By changing their dip to vertical, Þeistareykir 2e crosses two medium feed zones (in well ÞG-13 and well ÞG-18) and one active feed zone in ÞG-13 at 2360 m depth. At this depth, fractures analyzed with borehole televiewer imaging, show vertical to near-vertical faults dipping towards W/NW. After shifting Þeistareykir 1 to vertical, the fault crosses one large feed zone (in well ÞG-14) and three medium feed zones (in wells ÞG-15, ÞG-5 and ÞG-17), as well as an active feed zone in ÞG-15 at 1760 m depth. However, televiewer results from ÞG-15 at this depth interval show vertical to near vertical faults, striking nearly E-W which appears to be in contradiction to the already interpreted faults in the model. Figures 7 and 8 show the geological model where faults have been included.

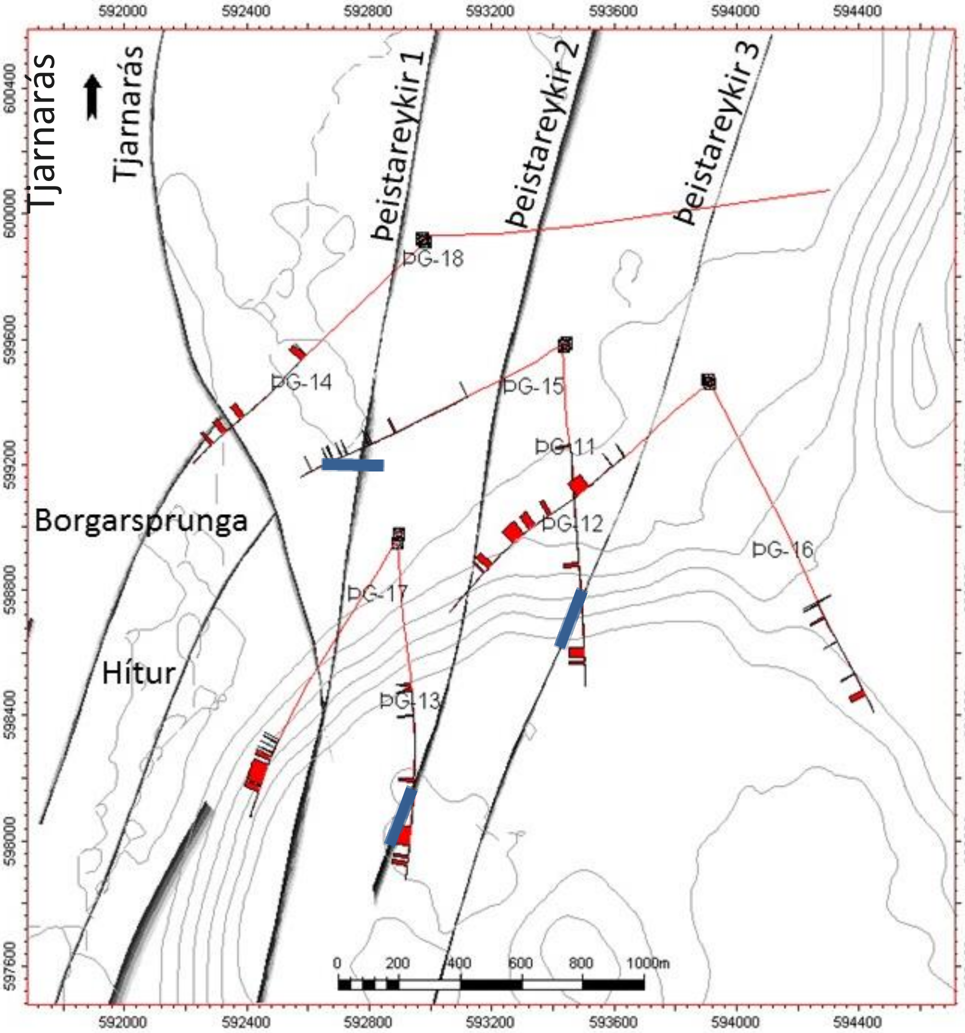

Figure 5. *The seven faults that are included in the geological model of Þeistareykir. Red intervals along the well pads show active feed zones based on spinner logging, and blue lines show the strike of faults (based on televiewer logging) in ÞG-11, ÞG-13 and ÞG-15, at the depths where the faults intersect the wells.*

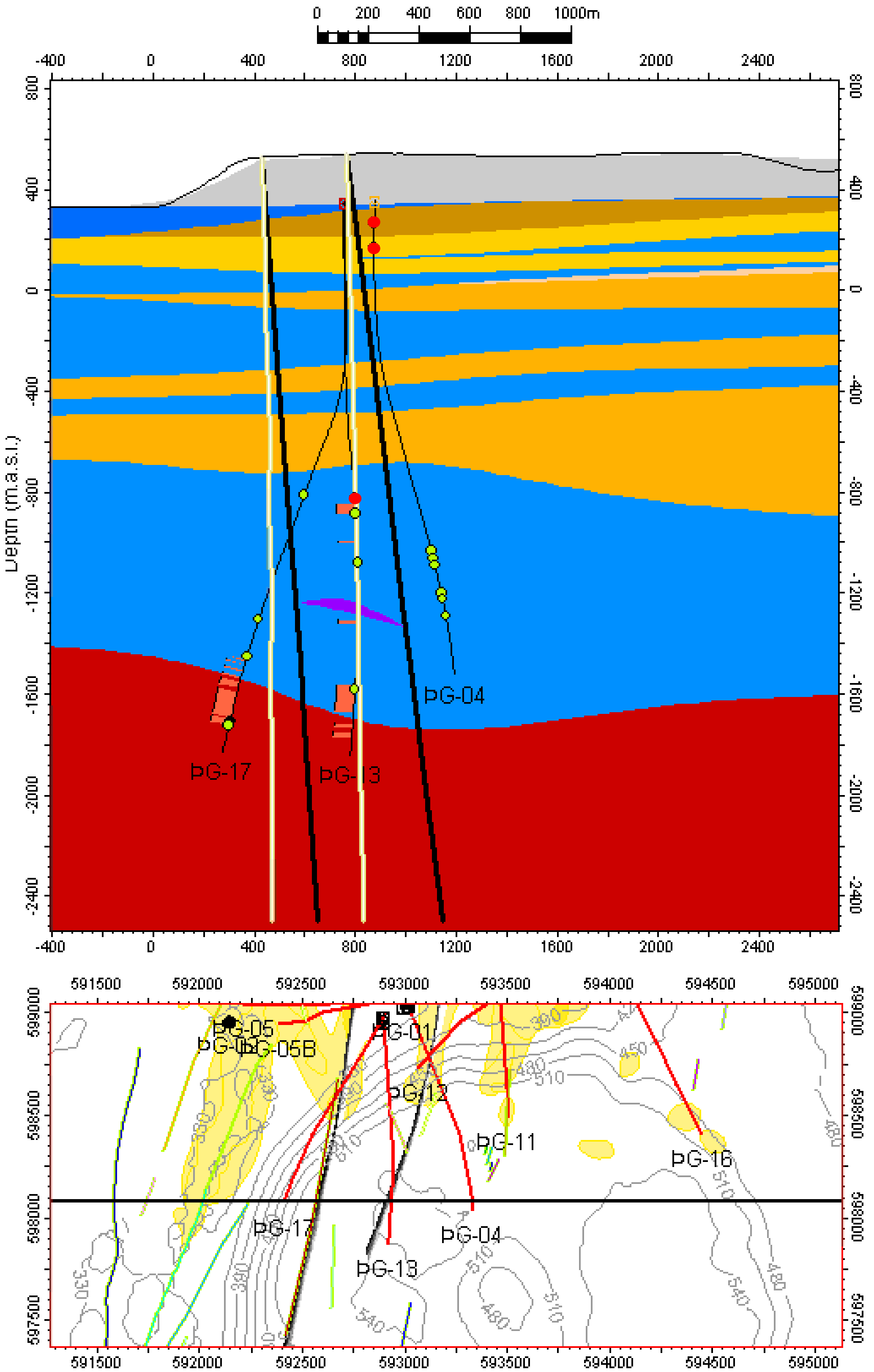

Figure 6. *The geological model and the previous dip of two fractures in the geological model (black line). The yellow lines represent the revised dip, based on locations of medium feed zones (green dots), large feed zones (red dots), televiewer data and active feed zone (red intervals) (see color legend for geological units in Figure 3).*

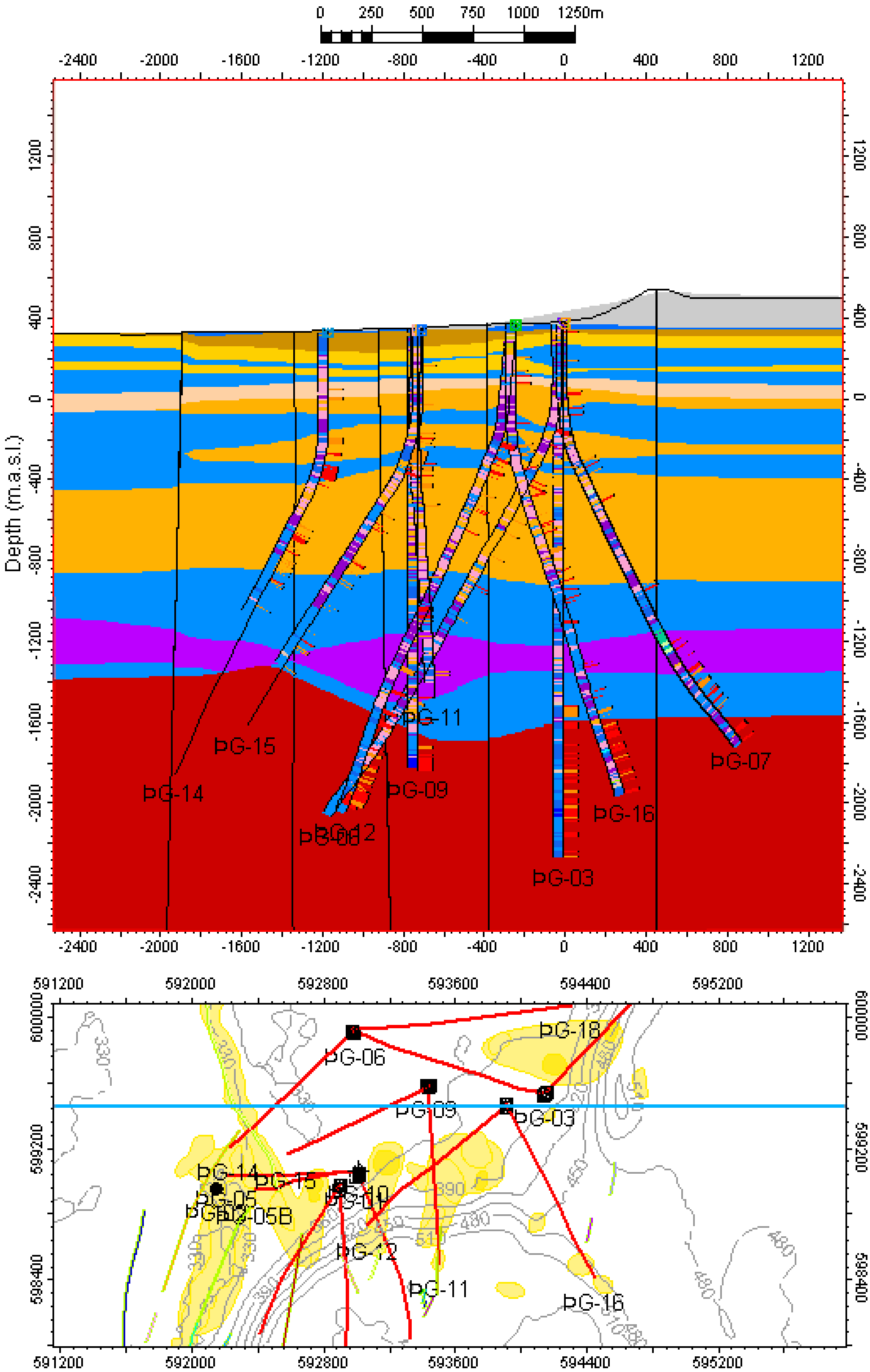

Figure 7. *E-W section of the revised geological model (see color legend in Figure 3).*

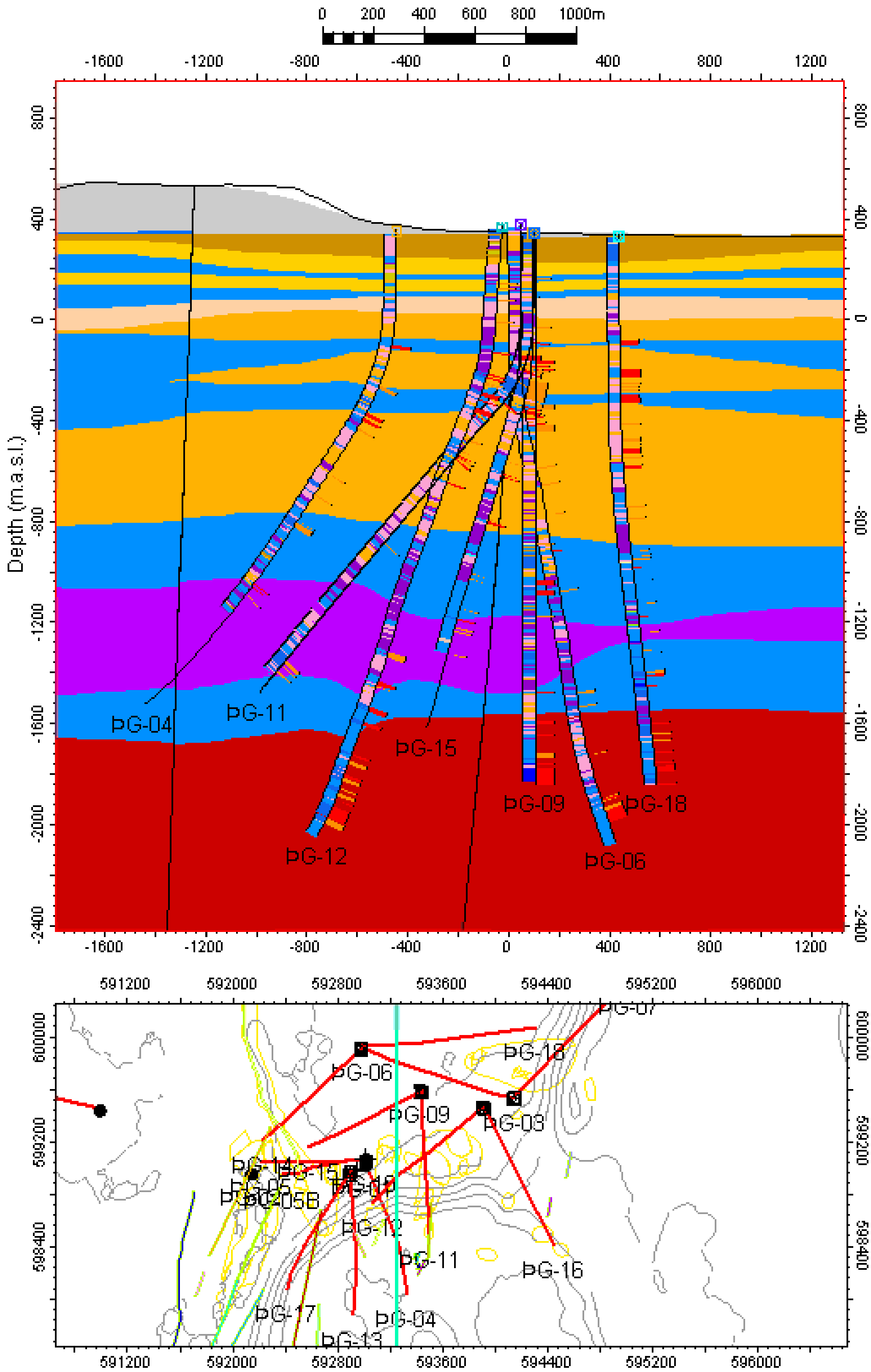

Figure 8. *N-S section of the revised geological model (see color legend in Figure 3).*

3.3 Felsic rocks

As mentioned in chapter 3.1, it was decided to exclude felsic rock from the geological model, but on the large scale the thin felsic units are barely seen. Instead, a discrete log was prepared for the model, where felsic/intermediate formations were analyzed or described in well reports and where gamma ray showed high anomaly, possibly reflecting felsic or intermediate formations. This was done in order to shed light on felsic units and observe the geometry and similarities in the formations across the geothermal field.

Altogether, seven felsic/intermediate formations were detected in the Þeistareykir wells. Some formations were present throughout a large part of the area, but some formations had very limited extent. An intrusion beneath Bæjarfjall is very prominent in the deepest 400–500 m of wells ÞG-13 and ÞG-17. Based on gamma logs, the intrusion could possibly be traced in wells ÞG-2, ÞG-15 and ÞG-14 (Figures 9 and 10).

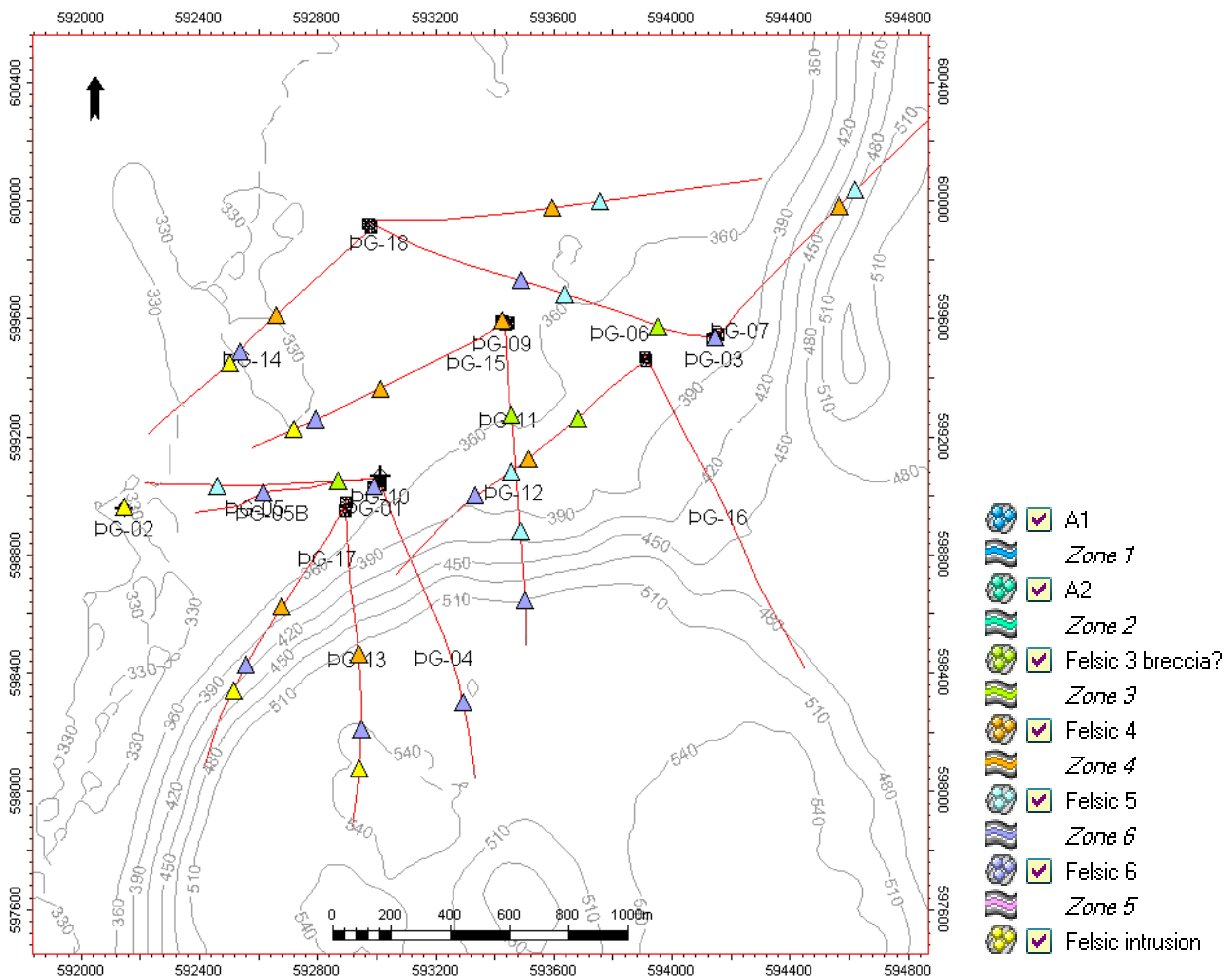

Figure 9. *Lateral extent of felsic/intermediate formations in Þeistareykir.*

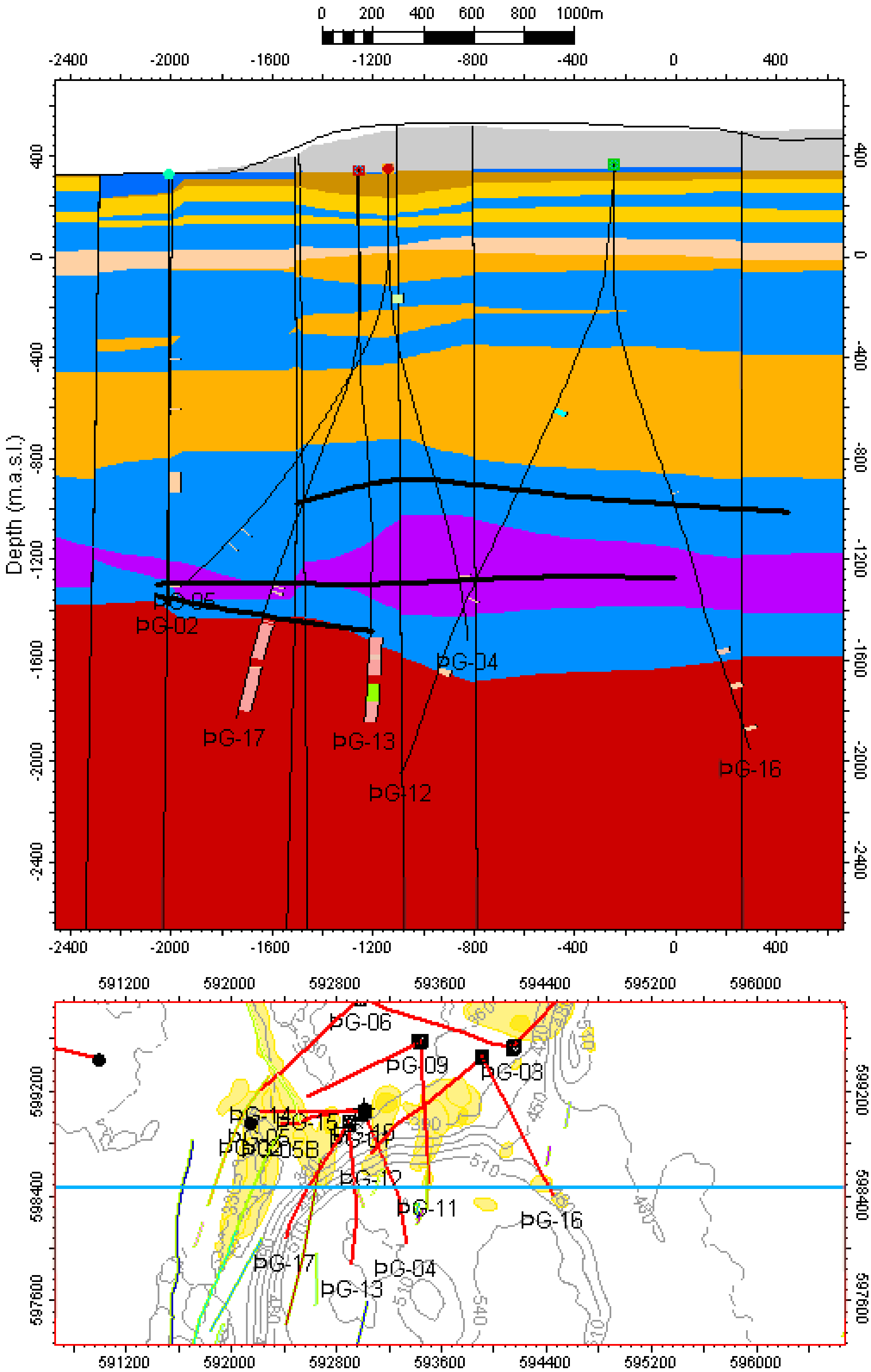

Figure 10. *A E-W section of the geological model of Þeistareykir. The interval log along well paths represents felsic or intermediate formations detected in the wells. Black lines represent the correlation between wells (see colour legend in Figure 3).*

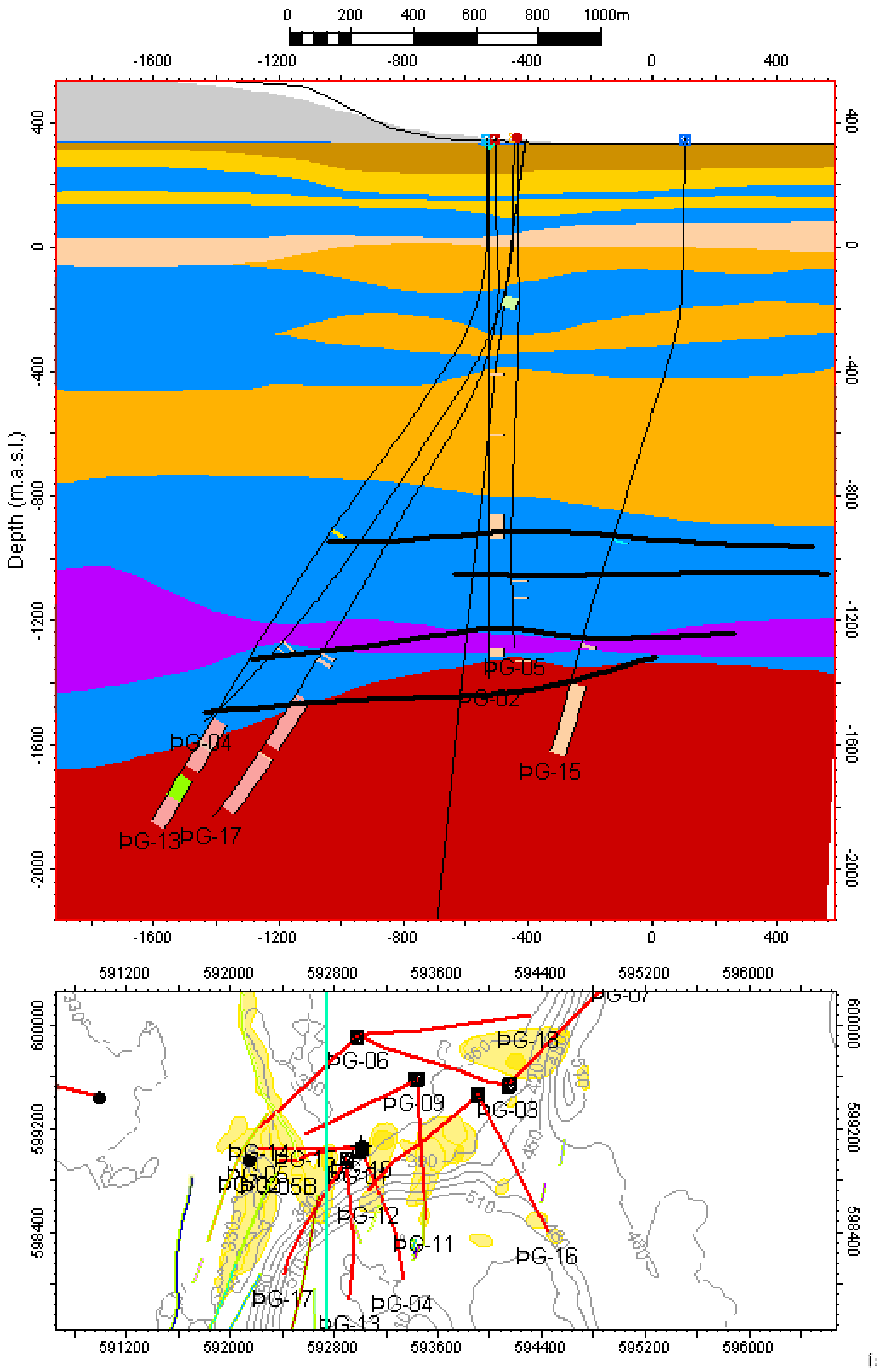

Figure 11. *A N-S section of the geological model of Þeistareykir. The interval log along well paths represents felsic or intermediate formations detected in the wells. Black lines represent the correlation between wells (see colour legend in Figure 3).*

4 Overpressured feed zones

Overpressurized feed zones have been seen in a few wells in Þeistareykir. Most of those wells are located on pad A (ÞG-1, ÞG-4, ÞG-5/5b, ÞG-10, ÞG-13 and ÞG-17) which is the pad located closest to mt. Bæjarfjall (Figure 11). In the first well, ÞG-1, this overpressurized zone was seen as a breccia formation, white in color and rich in precipitations, especially pyrite, quartz and calcite (Guðmundsson et al., 2002). This formation was seen in the other wells later drilled on the pad (Guðmundsson et al., 2007; Gautason et al. 2007; Guðjónsdóttir et al., 2016; Guðjónsdóttir et al., 2017; Sigurgeirsson et al., 2016). This formation was usually described the same, as a precipitation rich tuff or breccia. Calcite and pyrite rich and soft. In some wells a heat pulse was observed in return temperatures during drilling and in most or all a heat anomaly was seen in temperature logs. This over pressurization is thought to be connected to this formation. In the latest wells (ÞG-13 and ÞG-17), heavy mud was used for drilling and that seemed to eliminate the problems with the pressure during drilling. Well ÞG-10 was abandoned at 193 m depth due to this formation. On well pad C, over-pressurized feed zones were also cut in wells ÞG-3, ÞG-6 and ÞG-7 at similar depths as on well pad A (Figure 11). It is quite possible that this formation can be detected in more or all other wells in the area.

A comparison between location of the over-pressurized feed zones, geological model and a 3D inversion of MT/TEM resistivity model (from Karlsdóttir et al., 2012), reveal that the feed zones are located within the tuff-rich M1b formation in the geological model where the resistivity is relatively low (Figures 12–13).

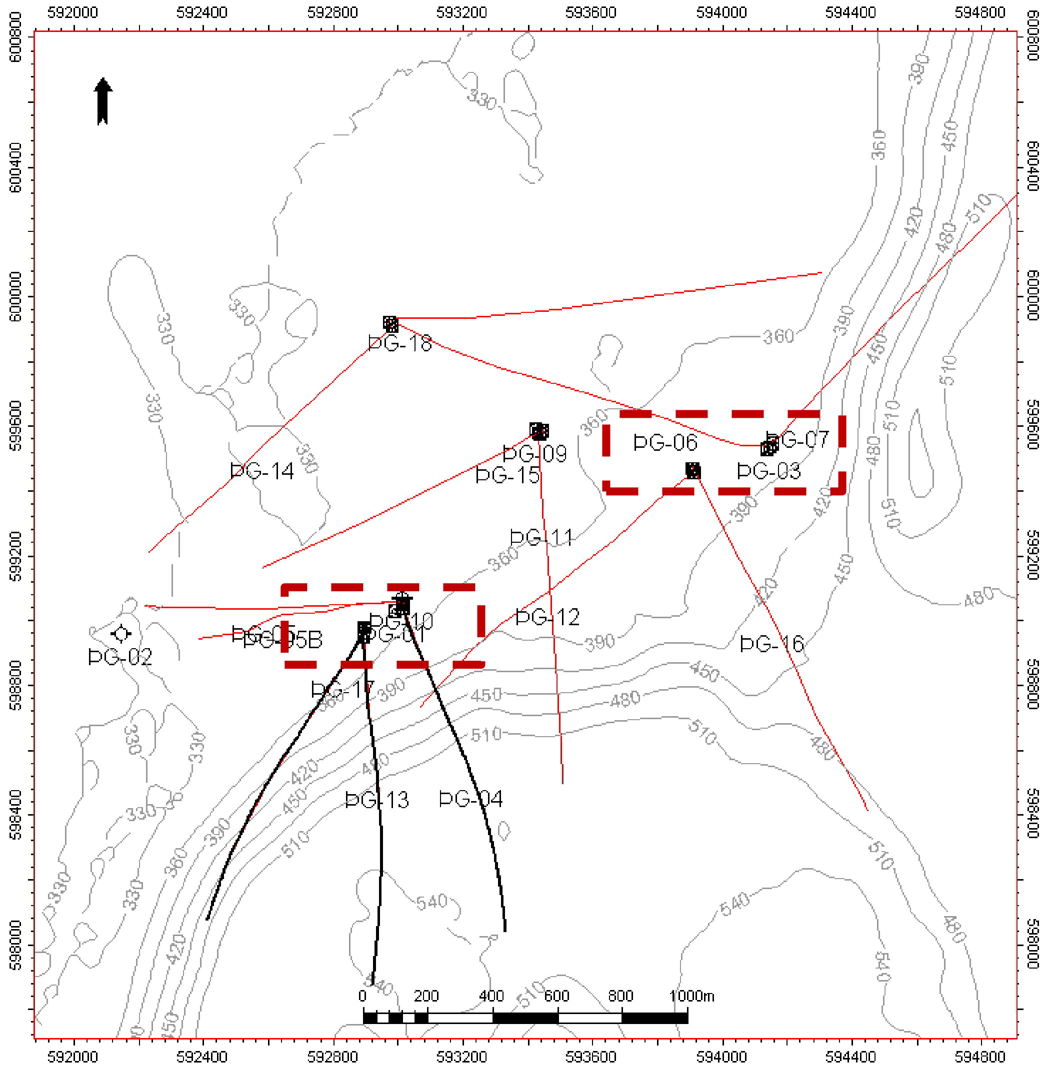

Figure 12. *Location of well pad A and well pad C, where over-pressurized feed zones were cut. The over pressure was also recognized in well ÞG-9 but did not cause any problem during drilling.*

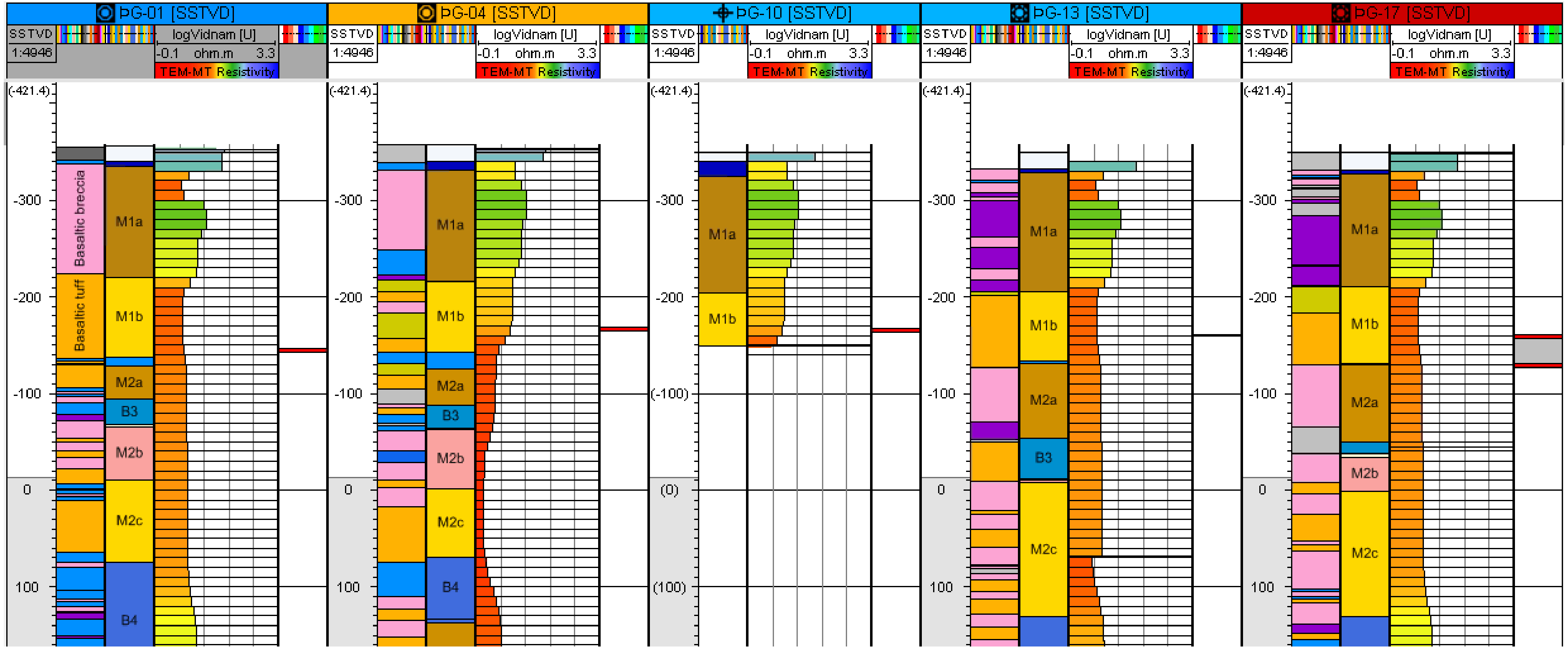

Figure 13. *A well log section showing lithological units of the geological model (to the left), cutting analysis from the wells (in the middle) and a resistivity log, based on a 3D resistivity inversion by Karlsdóttir et al. (2012). The red intervals represent the location of the over-pressurized feed zones detected in well pad A (see color legend in Figure 3).*

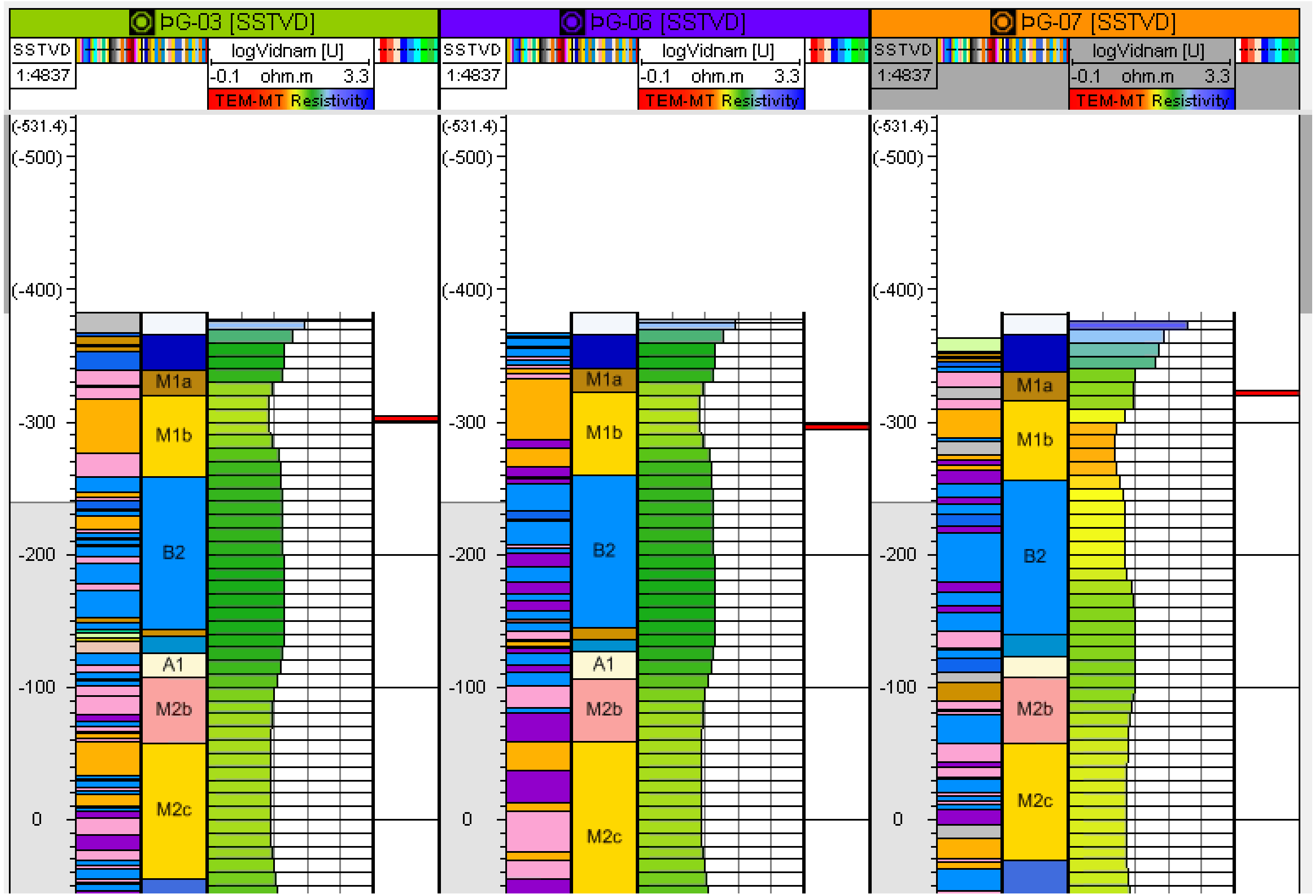

Figure 14. *A well log section showing lithological units of the geological model (to the left), cutting analysis from the wells (in the middle) and a resistivity log, based on a 3D resistivity inversion by Karlsdóttir et al. (2012). The red intervals represent the location of the over-pressurized feed zones detected in well pad C (see color legend in Figure 3).*

5 Alteration model

Several alteration models have been generated using various alteration information from the Þeistareykir wells;

- Cutting analysis with binocular stereoscope. Available for all wells. First occurrences of quartz, wairakite, epidote, prehnite, wollastonite, actinolite and depth where no calcite is seen has been imported to the model. In Figure 15, first occurrences of quartz and epidote are shown. Figure 16 shows two different depths where calcite disappears. In some wells (e.g. ÞG-7, ÞG-8 and ÞG-13) calcite appears again. Therefore, both upper and lower limit is also shown.

  A model with first occurrences of the most reliable minerals; quartz, wairakite, epidote and amphibole has been generated (Figures 17 and 18).
- XRD clay analysis. Available for ÞG-1 to ÞG-8, ÞG-15 and ÞR-7. A model with alteration zonation has been generated (Figures 19 and 20).
- Thin section analysis (Guðfinnsson, 2014). Available for ÞG-3 to ÞG-8. First occurrences of quartz, chlorite, prehnite, epidote, wollastonite, amphibole and depth where no calcite is seen has been imported to the model.

Although results from thin section analysis and XRD clay analysis are rather reliable and accurate, they are highly dependent on sample density and depth of the first thin section. Figure 14 shows the sample density of thin sections and XRD clay analysis. Where data density is low (e.g. in the upper part of ÞG-7), it was decided to transfer the data from neighboring wells.

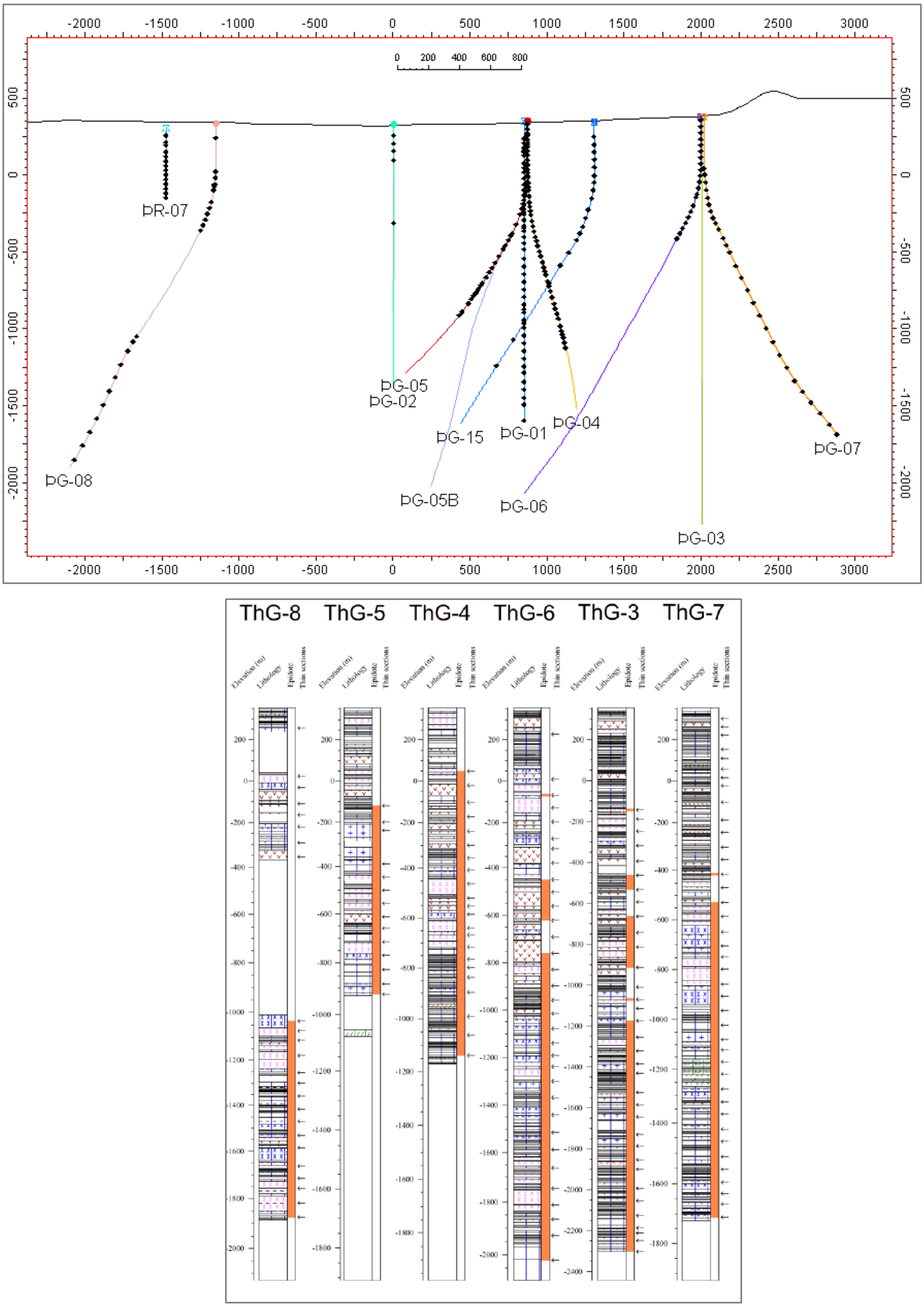

Figure 15. *Upper figure: Black dots show the XRD sample distribution of the wells. Lower figure: Black arrows show the thin section sample distribution of the wells (Guðfinnsson, 2014).*

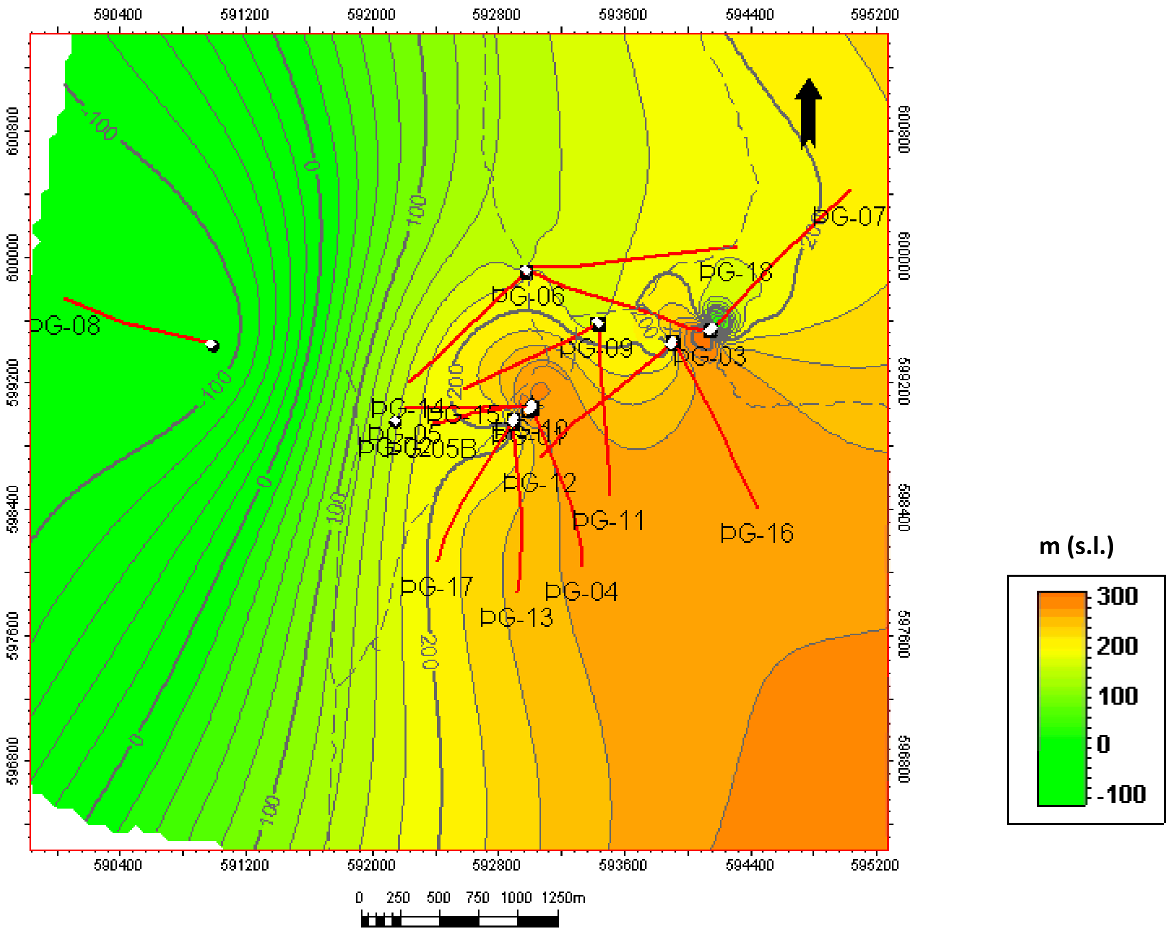

Figure 16. *First occurrences of quartz based on cutting analysis. White dots represent the occurrence of the alteration mineral in each well. Contour lines are shown every 20 meters.*

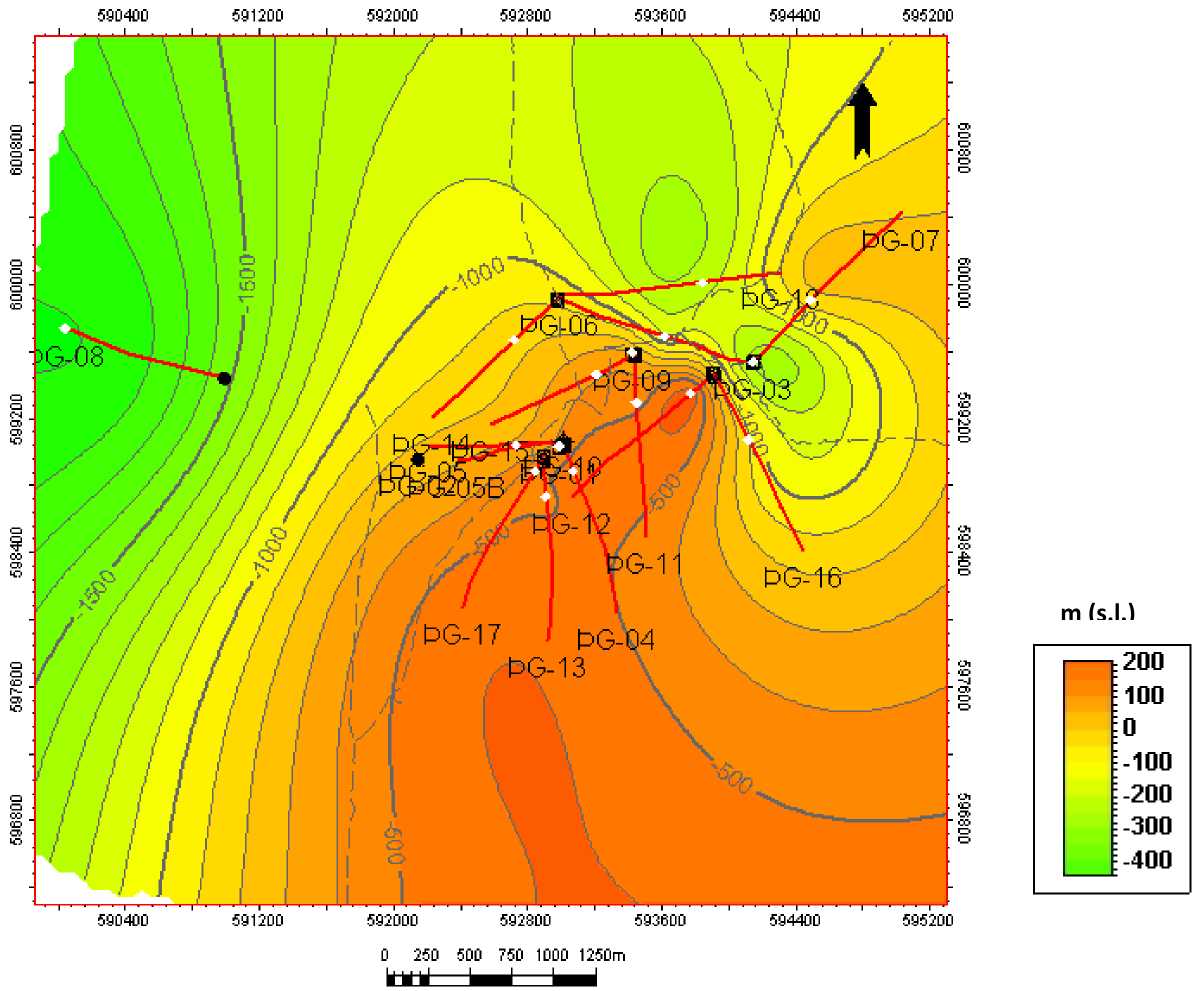

Figure 17. *First occurrences of epidote. Based on cutting analysis. White dots represent the occurrence of the alteration mineral in each well. Contour lines are shown every 20 meters.*

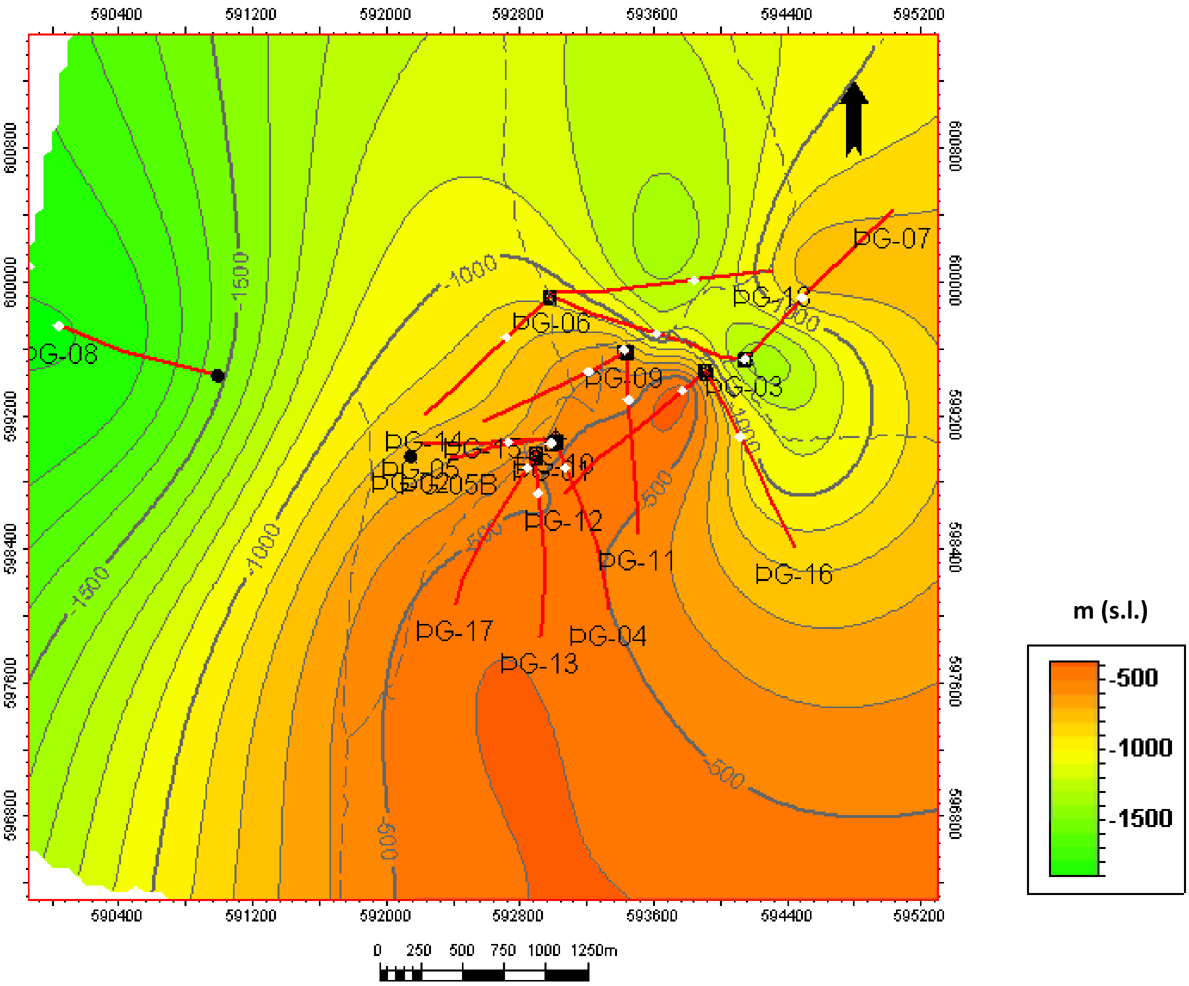

Figure 18. *The depth where calcite disappears (upper limit). Based on cutting analysis. White dots represent the disappearance of calcite along the well path and contour lines are shown every 100 meters.*

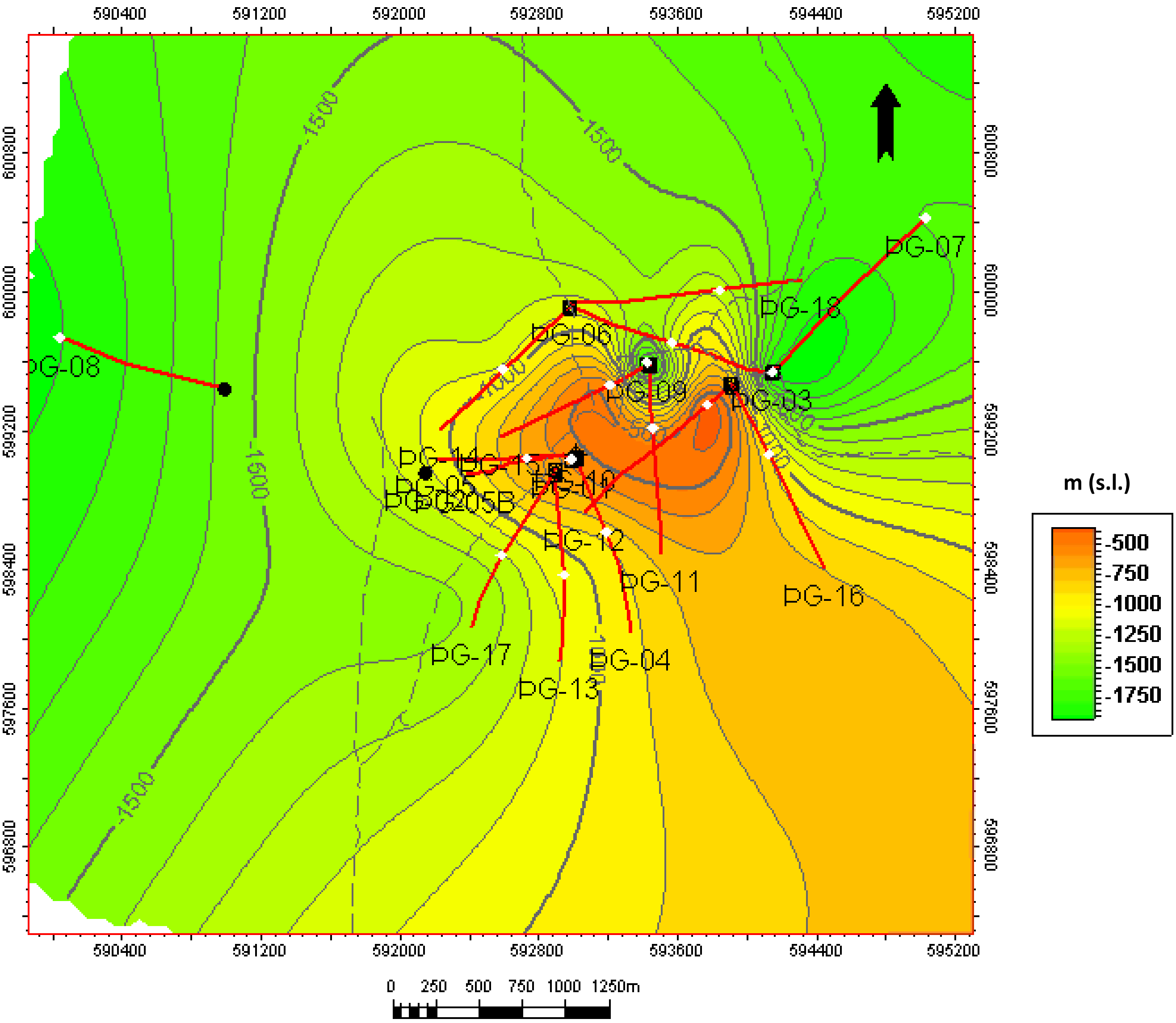

Figure 19. *The depth where calcite disappears (lower limit). Based on cutting analysis. White dots represent the disappearance of calcite along the well path and contour lines are shown every 100 meters.*

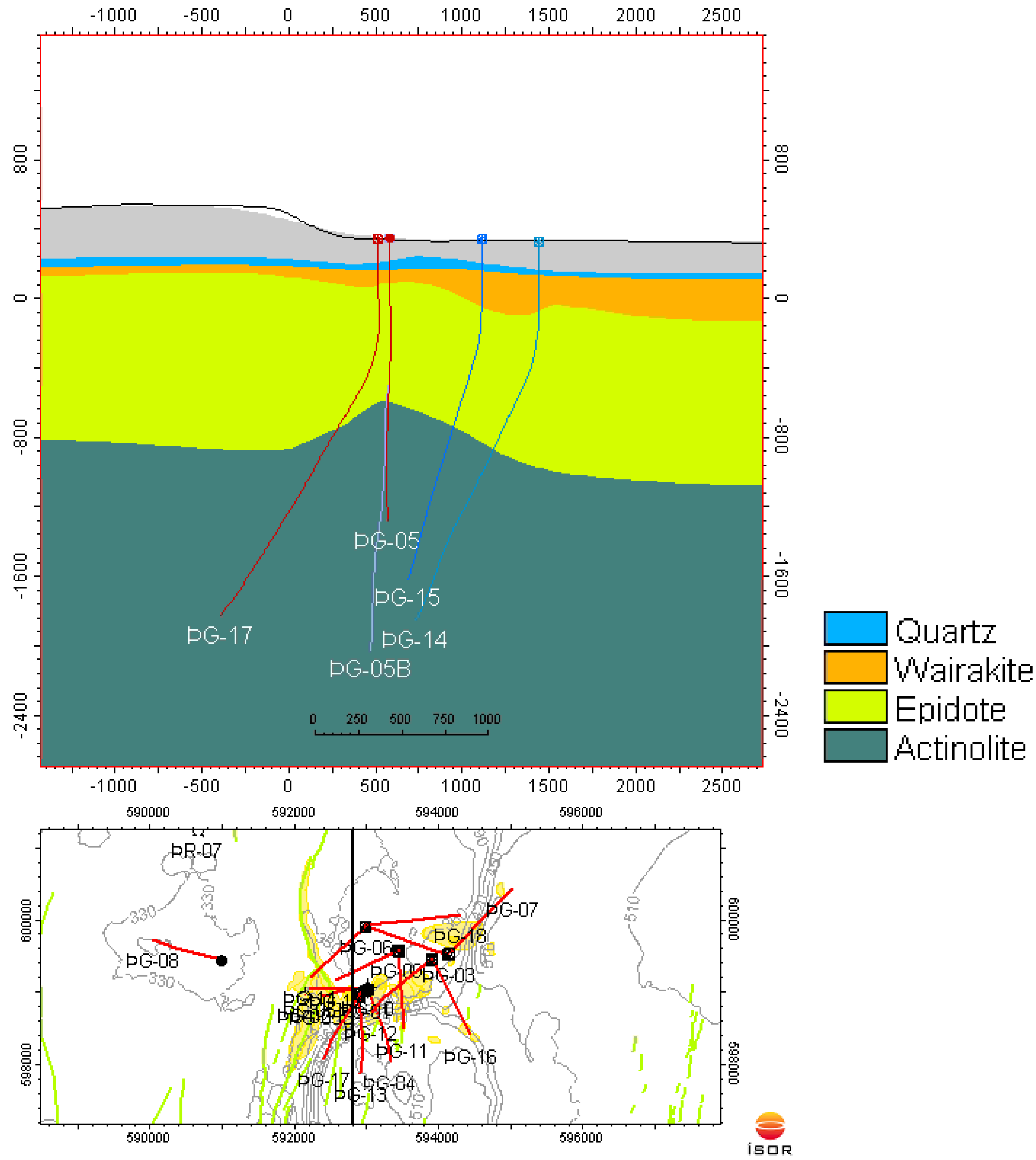

Figure 20. *Alteration model based on first occurrences of quartz, wairakite, epidote and amphibole (N-S section).*

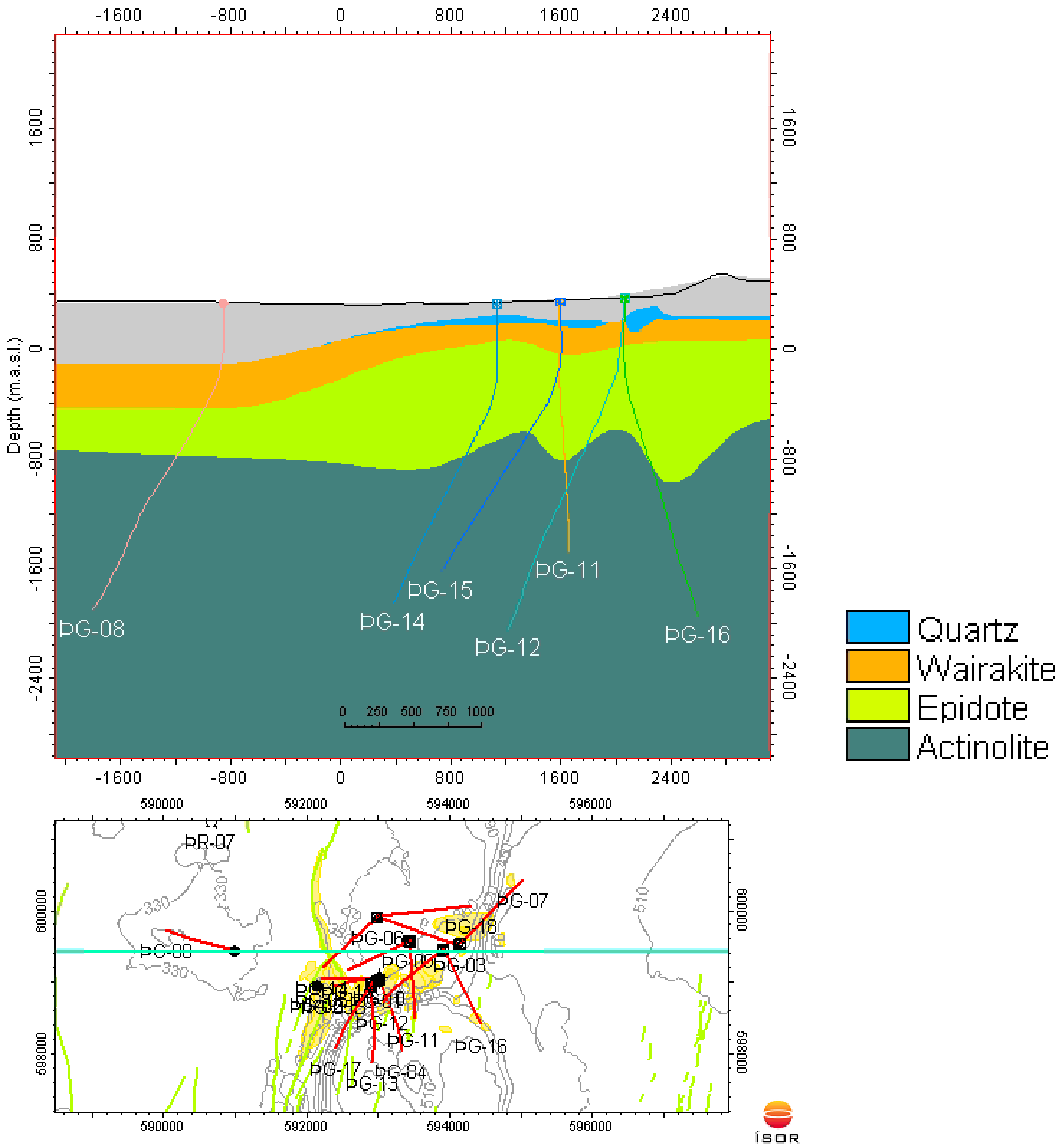

Figure 21. *Alteration model based on first occurrences of quartz, wairakite, epidote and amphibole (N-S section).*

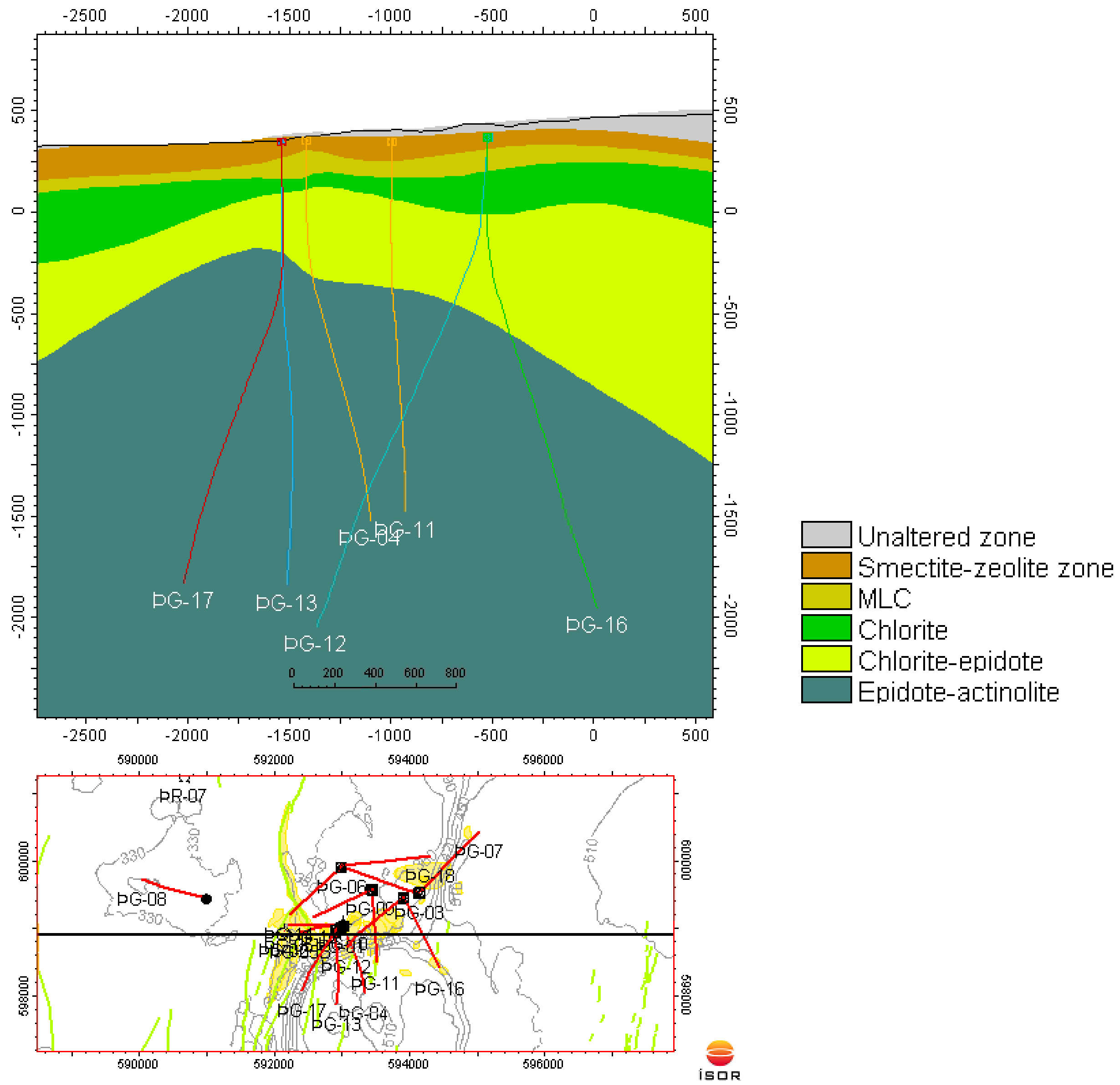

Figure 22. *E-W section through alteration model based on XRD clay analysis and cutting analysis of epidote.*

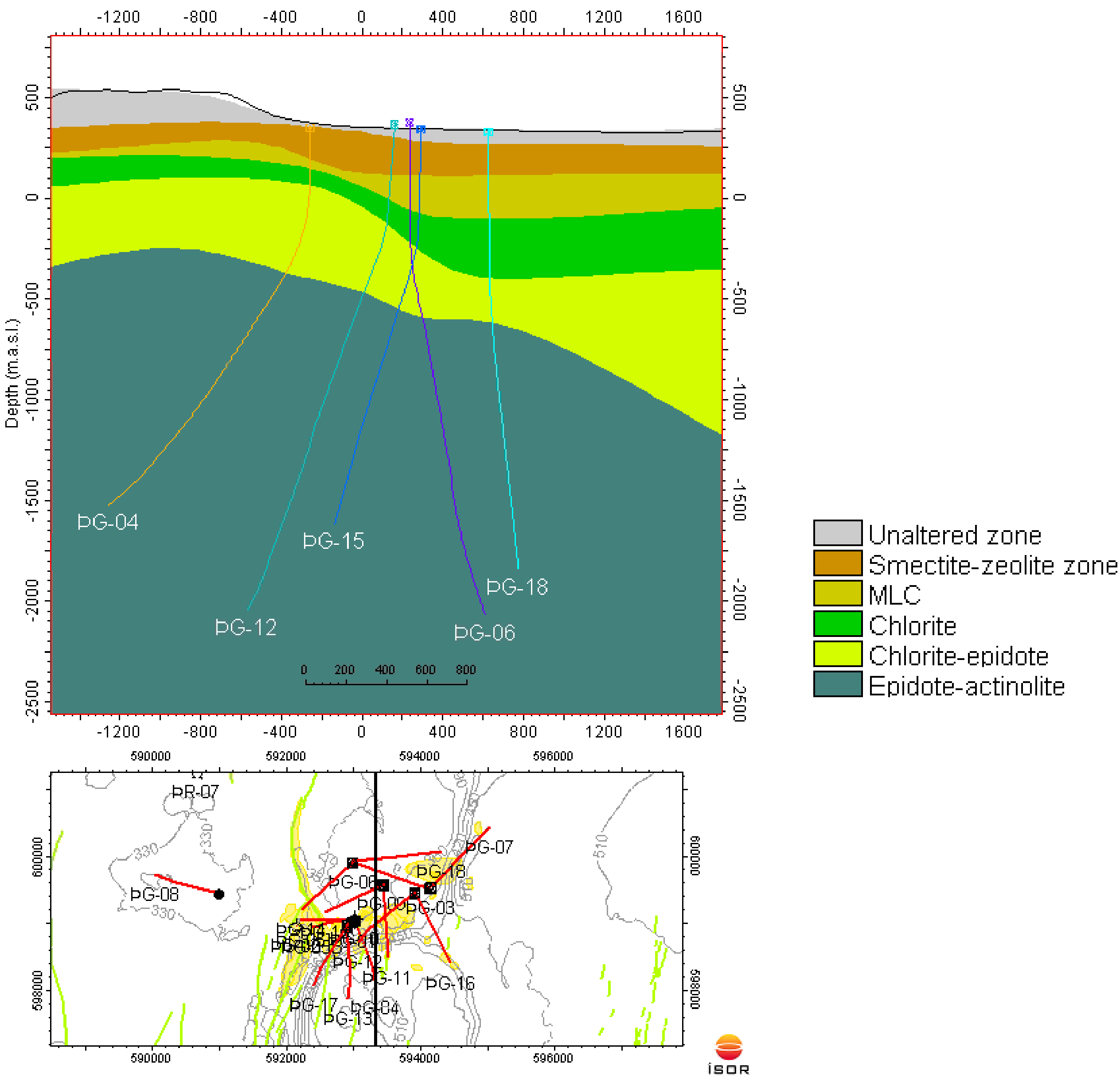

Figure 23. *N-S section through alteration model based on XRD clay analysis and cutting analysis of epidote.*

5.1 Outliers in alteration zonation

The alteration zonation in Figures 19 and 20 is based on stratification of smectite, mixed layer clays, chlorite and amphibole which have been arranged into zones based on their reference temperature. Generally, minerals with increasing reference temperature appear with increasing depth in the wells. However, in four wells (ÞG-4, ÞG-6, ÞG-7 and ÞG-15), MLC and smectite appear again deeper in the well, after the occurrence of chlorite (Table 2). As the zonation in the model is based on first occurrences of the alteration minerals, the second appearance of minerals cannot be outlined in the simple alteration zonation model. However, as this could be an indicator of cooling in the system and therefore could have impact on further development of the geothermal field. An example of this is displayed along the well paths in Figure 21.

Table 2. *Depth ranges of MLC and smectite where it appears again deeper in the well.*

Well	Alteration zone	MD (m)
ÞG-4	MLC	1060 1090
ÞG-6	MLC	310 350
ÞG-7	MLC	840 894 950 1250 2290 2400 2494
ÞG-15	Smectite	798 1000

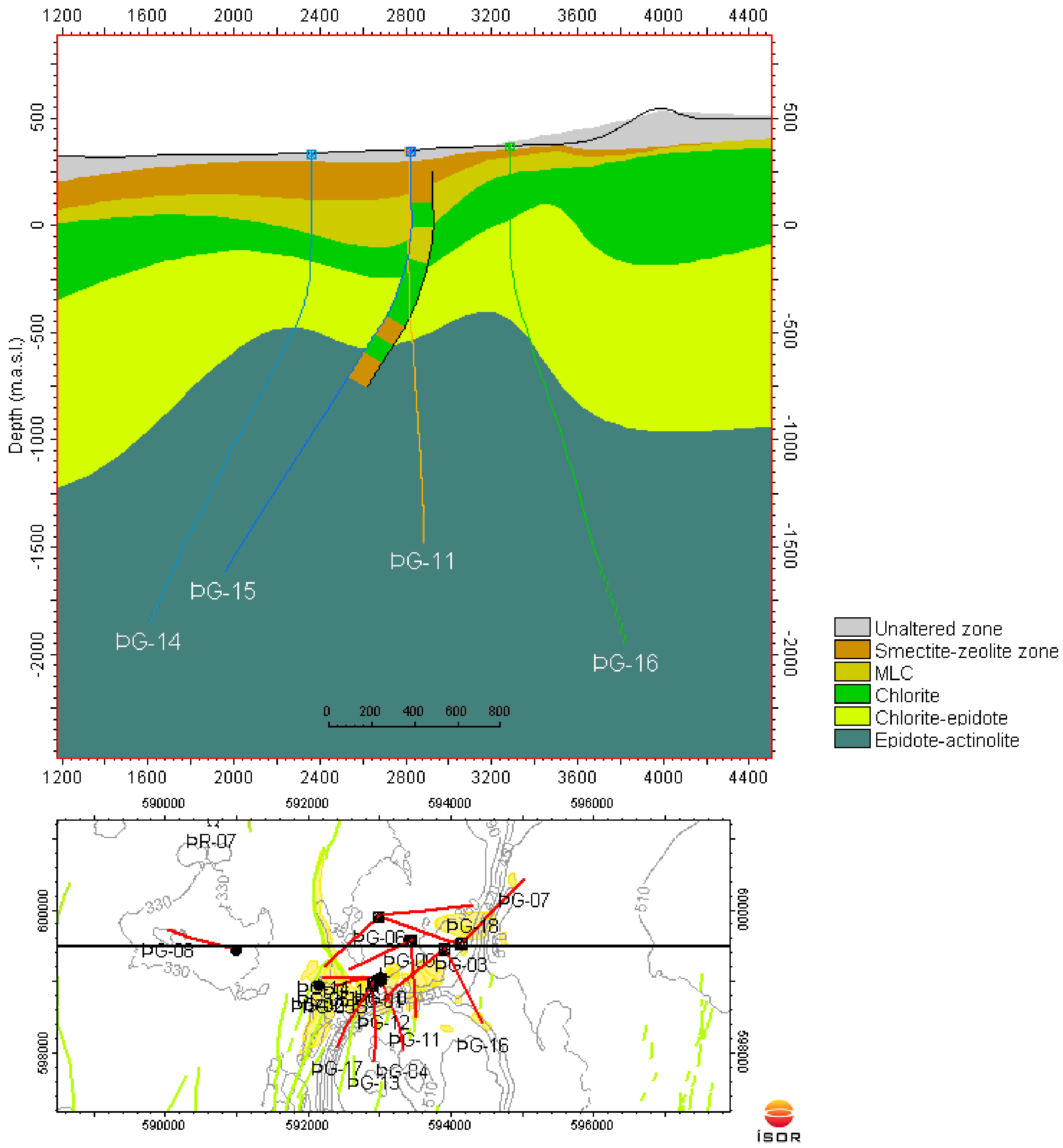

Figure 24. *Alteration zonation of Þeistareykir based on XRD analysis. In well ÞG-15, smectite is seen at 798 and 1000 m depth, which is unusually deep compared to other wells in the area. NOTE: The logs only reflect the clay analysis of the samples.*

5.2 Alteration temperature

An alteration temperature model was created based on temperature dependent minerals that have been listed in the previous chapter. Alteration temperature logs along the well paths have been imported to the model, where all available temperature dependent minerals for each well are included (Table 3). For the older wells of Þeistareykir, XRD analysis are included to the logs, whereas alteration temperature of the newer wells (ÞG-9 to ÞG-18) are only based on binocular stereoscope analysis. For the simple alteration model, the first occurrences of quartz, wairakite, epidote, wollastonite and amphibole were included. Their analyses are the most reliable and consistent along all wells but additional information is seen on the well logs (Figures 23 and 24).

Table 3. *Alteration temperature of each alteration mineral.*

Alteration mineral	Alteration temperature (°C)
Quartz	180
Wairakite	200
MLC*	200
Chlorite*	230
Epidote	240
Wollastonite	260
Amphibole	280
No calcite	290

*Only available for ÞG-1 to ÞG-8, ÞG-15 and ÞR-7.

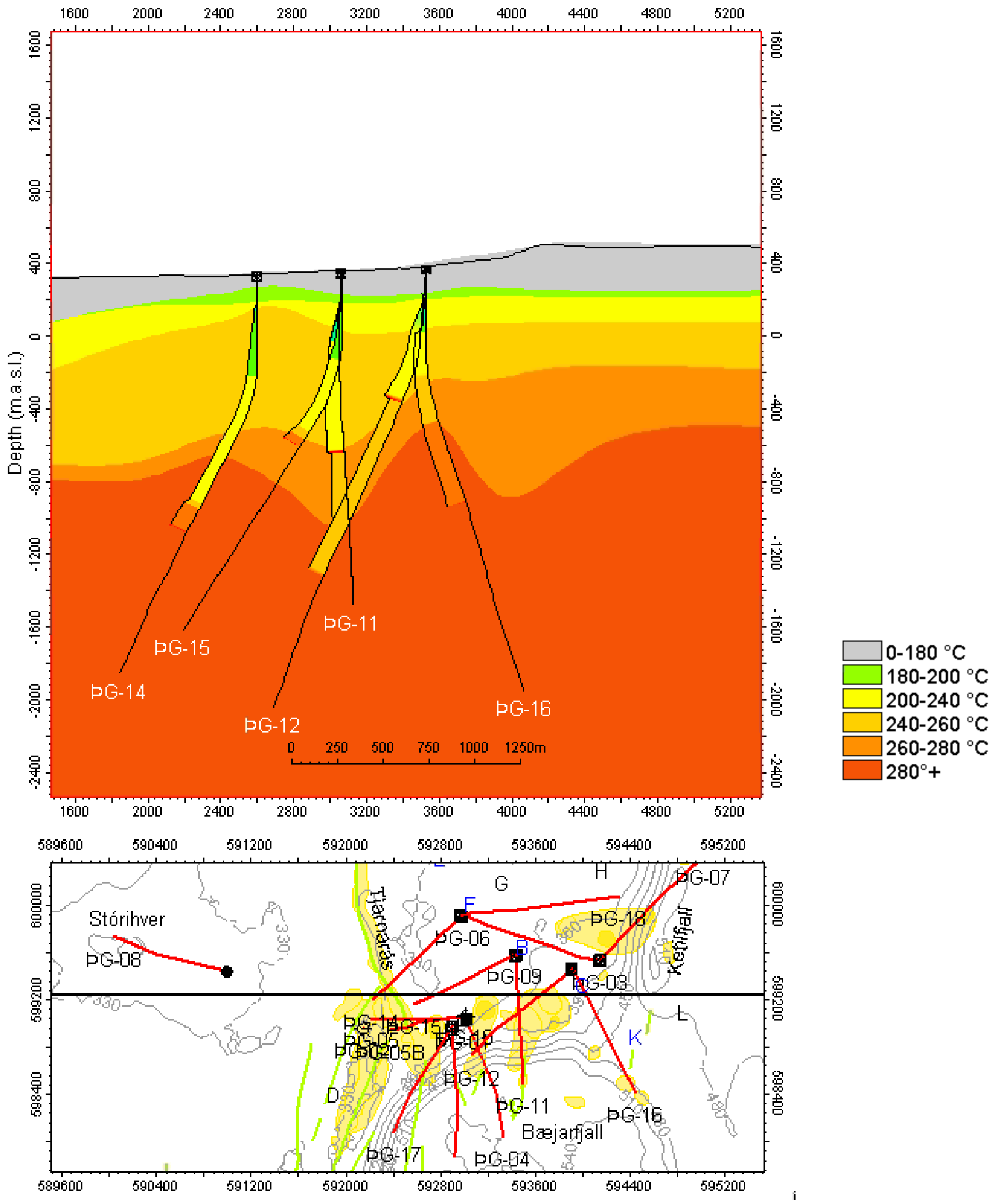

Figure 25. *Alteration model and well logs showing different alteration temperature (E-W section).*

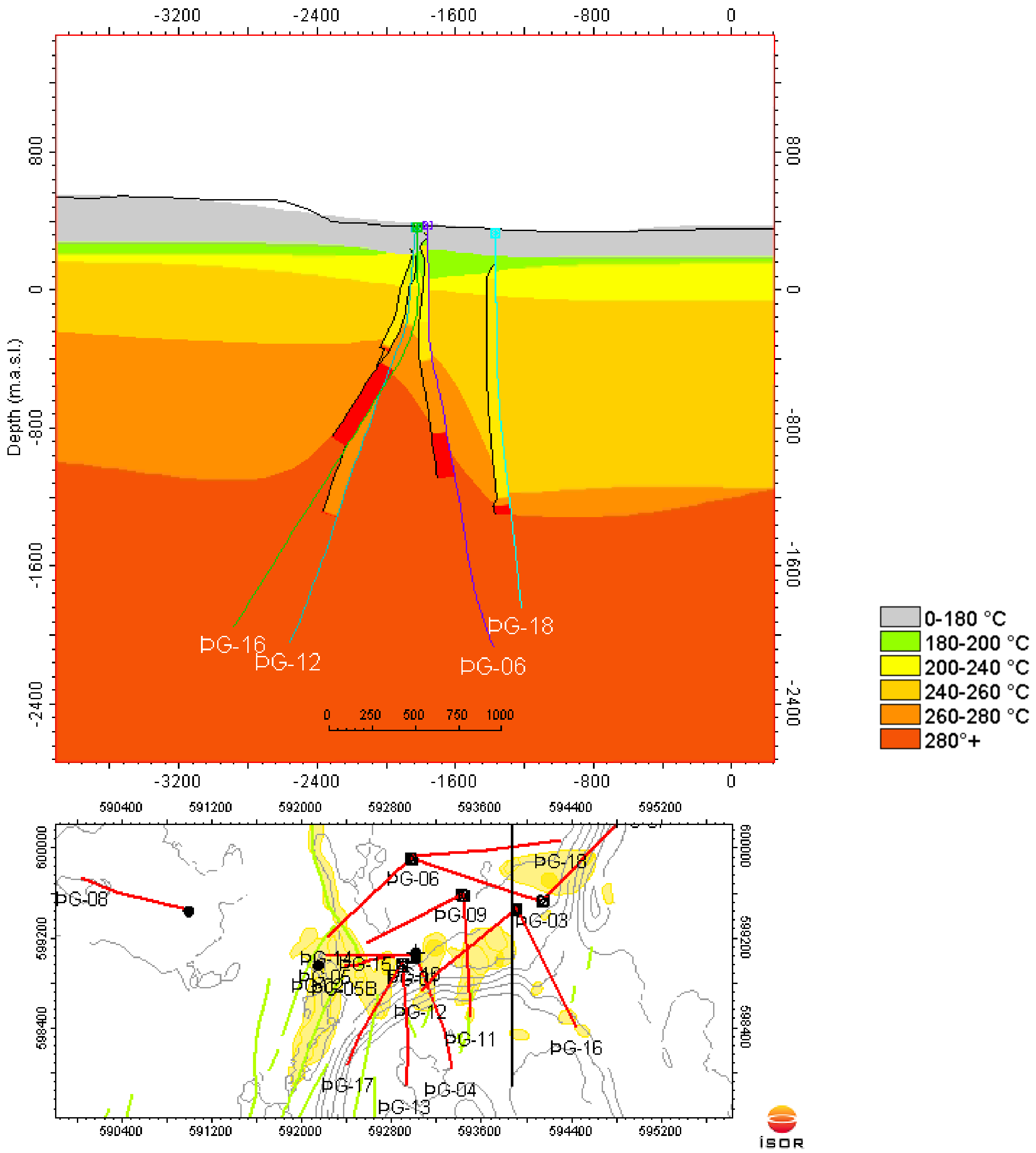

Figure 26. *Alteration model and well logs showing different alteration temperature (N-S section).*

6 Summary

Additional lithological and structural data that has been imported to the Þeistareykir geological model, has resulted in a revised geological and alteration model.

- The geological model is composed of seventeen lithological units and seven faults and fissures, which are based on the previous models.
- Relative sizes of feed zones, active feed zones and borehole televiewer data have been added to the model and are compared to the dip and dip direction of the surface fissures and faults.
- Overpressurized feed zones, detected at shallow depths in eight wells in the Þeistareykir geothermal field, have been mapped and imported to the Petrel model. They lie within the tuffrich hyaloclastite formation M1b within a zone of rather low resistivity.

Alteration models were created from different sources; cutting analysis, thin section analysis and XRD clay analysis. The alteration models allow a comparison between wells, where the depth to alteration minerals outline the geometry of the geothermal field. They show the alteration updoming beneath Bæjarfjall and a sign of a lower temperature gradient with increasing distance to the N and NW. Outliers in the alteration zonation have been mapped and presented on cross sections. They could indicate a local cooling in the system and should be preserved in the future work.

In the geothermal field of Þeistareykir there are still many unanswered questions. To improve the model even further it would be ideal to do more research on the structure, tectonics and alteration. For the wells ÞG-3 to ÞG-8, thin sections have been made and analyzed (Guðfinnsson, 2014). The analysis was imported to the Petrel model with the aim of supporting alteration and geological correlations. Marker layers between 200 and 400 m below sea level (from Guðfinnsson, 2014), were compared to the large scale lithological units generated from cutting analysis. No clear relationship was seen between marker layers and the large scale lithological units. Denser thin section analyses from the Þeistareykir area would perhaps reveal more comprehensive geometry of the marker layers, which could be useful for the geological correlations. Therefore, it would be very beneficial to the project to add thin sections from the newer wells but some of them were drilled into new areas. This would improve the geological model as well as the alteration model.

In order to improve the intrusion model, a further analysis of the cuttings, thin sections and borehole logs would be necessary. As felsic formations have now been excluded from the lithological logs, a separated facies model can be generated in Petrel. Using that module, the formations are easier to constrain than building a simple model with horizons. Facies model would reflect the geometry of different felsic formations.

Another part of this project was to calculate injectivity indexes for feed zones in the wells as well as inserting results from televiewer logs into the Petrel software platform. More structural data would allow further joint interpretation and improve the fault model for a better understanding of the flow of fluids in the system. A short report on fluid inclusions from ÞG-15 (Helgadóttir, 2018), showed some evidence of inverted temperature profile in the well. To further confirm this, it is suggested that further research this inverted temperature profile is carried out. To do so, fluid inclusions from more wells is recommended.

List of suggestions:

1. Update and define in more details the structural elements, based on televiewer analysis and MEQ and connect with surface mapping. This would improve a fluid flow model.
2. Analysis of more thin sections to evaluate the outliers in alteration and estimate the possible temperature reversal, as well as newer wells in the region.
3. Addition of fluid inclusion analysis, both from ÞG-15 to confirm the reversed temperature, but also from other wells in the area.
4. Improve the intrusion model with further, detailed cutting and thin section analysis, and merge in to the geological model. Joint interpretation of both geological and geophysical data.
5. Further analysis of the over pressurized zones. More detailed cutting analysis, adding thin sections. Looking more into other data that could indicate this increased pressure, i.e. geophysical data.

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