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FLUID FLOW PROCESSES IN THE BEPPU GEOTHERMAL SYSTEM, JAPAN

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ABSTRACT

The Beppu geothermal system comprises two out-flow zones on the east side of a high temperature resource *area* situated beneath the volcanoes of Tsurumi and Garandake. The deep geothermal fluid is inferred to have a temperature of at least 250 - 300 °C and a chloride concentration of at least 1400 - 1600 mg/kg. The chemical and physical differences between the fluids in the two outflow zones are due to differences in the way the fluid rises from beneath the volcanoes. Fluids in the southern, Beppu, outflow zone have evolved from the deep parent fluid predominantly by dilution with cold groundwater. However the northern, Kamegawa, outflow zone is dominated by steam loss from the parent fluid, and the formation of steam-heated groundwaters at shallow depth.

INTRODUCTION

The Beppu geothermal system is situated on Kyushu Island at the northeast end of the Ryukyu volcanic arc. Beppu city has grown around its onsen (hot springs) and jigoku (steaming ground) on the lower flanks of the Late Quaternary andesitic centre of Mts Yufu, Tsurumi, and Garandake. The first geothermali wells were drilled during the 1380s, and by 1924 over 1000 wells were extracting 400 kg/s of hot water. There are now close to 3000 wells with a total mass flow of about 600 kg/s. The wells range up to 700 m depth and encounter temperatures in excess of 200 °C.

A complete review of the natural state of the Beppu geothermal system, and its response to exploitation has been circulated within Japan as a special publication of the Geophysical Research Station of Kyoto University, Beppu (Allis et al., 1988). A shortened version suitable for publication in an international journal is presently being prepared (Allis and Yusa, in prep.). This paper reports on one aspect of the recent review: viz. the processes affecting the geothermal fluid in the upflow and outflow parts of the system.

DISTRIBUTION OF THE THERMAL ACTIVITY

Figure 1 shows the extent of thermal activity at Beppu. The westernmost activity occurs near the summits of Mts Garandake and Tsurumi. Recent surveys using aerial infrared methods suggest the steam-heated ground and superheated fumaroles of Garandake have a heat output of around 20 MW, compared to around 1 MW from the Tsurumi fumarolic *area* (Yuhara et al., 1987). At lower elevations there *are* also two main areas of thermal activity. On the southern side of the system there is the Beppu thermal zone, which originally comprised hot springs and small areas of weakly steaming ground. This thermal zone is closely associated with the Asamigawa Fault, with hydrothermally altered andesite exposed along its southern, upthrown side (the Kankaiji Propylite).

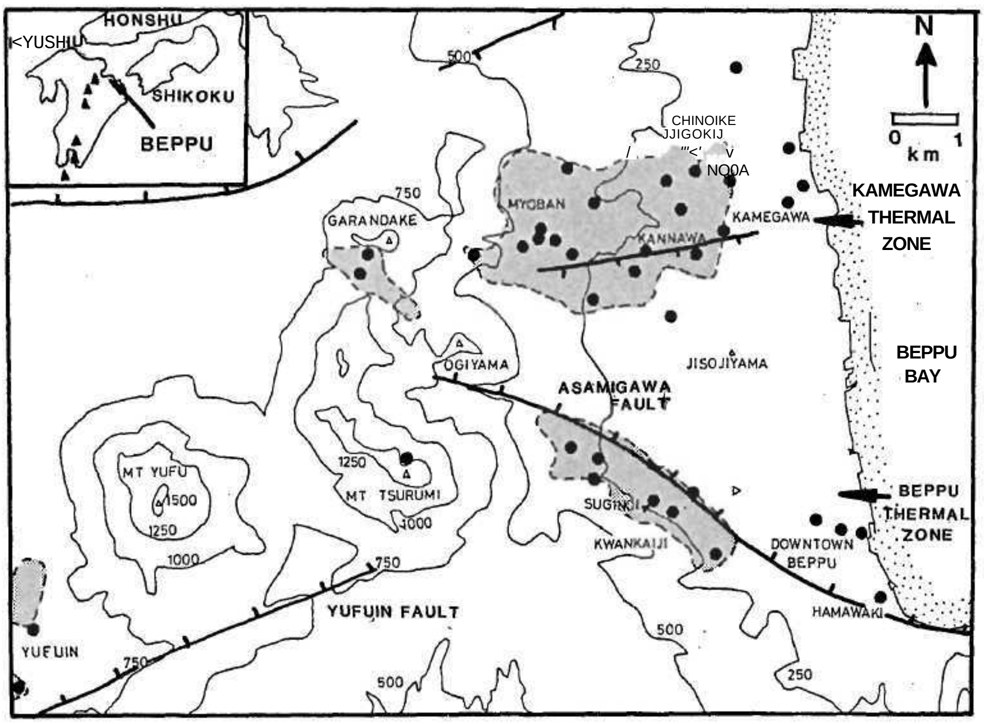

Figure 1: Distribution of thermal activity in the Beppu geothermal system prior to exploitation (dots). Shading denotes areas of surface hydrothermal alteration.

The hot springs of downtown Beppu wire located near the seaward, eastern end of this thermal zone. Although there is no data on the original hot springs, well data from this area indicates a maximum temperature of around 65 °C. Between 2-4 km north of the Beppu thermal zone is the Kamegawa thermal zone (Figure 1). The original hot springs in the downtown Kamegawa area were probably close to boiling. These no longer exist, but 1 km further inland is the only naturally flowing hot spring remaining in the Beppu system - Chinoike Jigoku. The spring is in fact an overflowing pool, with a heat output of 7 MW, a pH of about 2, and a hematite precipitate which gives the pool a bright red colour (Yuhara et al.,1978). Even further west in the Kamegawa thermal zone, there is a relatively broad area containing patches of steaming ground, and zones of intense, acid-sulphate alteration.

SUBSURFACE TEMPERATURES

Apart from bottomhole temperatures measured during drilling, there *are* virtually no temperature profiles in Beppu wells after they have equilibrated with countryrock temperatures. The bottomhole temperatures themselves have to be treated cautiously because of the presence of subhydrostatic vertical pressure gradients at higher ground elevations, and the tendency for downflows between aquifers. Many wells are boiling at the wellhead when discharging, and excess steam in the discharge fluid combined with difficulties in making accurate measurements makes the wellhead enthalpy an unreliable indicator of feedzone temperature. After culling out what was considered to be unreliable subsurface temperature data, a temperature map at 100 m below sea level was compiled (Figure 2). This map clearly shows the two thermal zones apparent from the surface thermal activity. Both thermal zones have temperatures in excess of 200 °C towards the western edge of the drilled area of Beppu City, and one well in the Beppu thermal zone had a maximum temperature of 248 °C at 300 m below sea level immediately after drilling.

The isotherms in Figure 2 point to a high temperature resource area beneath Mts. Tsurumi and Garandake, One 600 m deep well drilled near the summit area of Garandake by the Japan Geothermal Development Promotions Centre (1979), indicated 250 °C at the bottom of the well (i.e. at an elevation of 250 m above sea level). Much cooler temperatures in a well 1 km west of Garandake, and a second relatively cool well 3 km south of Tsurumi suggest the high temperature anomaly is confined to beneath the two volcanoes, with the main outflow being to the east.

Application of the Giggenbach (1986) Na-K-Mg geothermometer to the geothermal fluids at Beppu also indicates deep temperatures in excess of 250 °C (Figure 3). Although the more dilute fluids are scattered on this plot, the higher chloride, hotter waters suggest deep temperatures in the range 250 to 300 °C.

FLUID CHEMISTRY

The onsen of Beppu are noted for their diverse chemical characteristics. Waters from the Beppu thermal zone tend to be near-neutral, with higher bicarbonate and lower chloride concentrations than the Kamegawa thermal zone. The Kamegawa thermal zone waters range from very low pH, sulphate rich waters at higher elevations, to relatively chloride-rich waters O2000 mg/kg), which may be acidic or near-neutral. These variations can be seen in the hexa-plots of Figure 4. the acidic waters of the Kamegawa thermal zone coincide with the areas of steaming ground and intense surface alteration, indicating that they are a consequence of oxidized H_2S in steam-heated groundwaters. Downflows of these waters result in the mixed, chloride-sulphate waters discharging from some wells.

The amount and composition of gas in steam separated at the wellhead around the Beppu geothermal system is very variable (Koga and Noda, 1973). Gas concentrations range up to 10% by weight, with significantly higher concentrations occurring in the Beppu thermal zone than in the Kamegawa thermal zone. This is consistent with the higher bicarbonate concentrations in the Beppu thermal zone waters, and the general predominance of CO_2 in the gas.

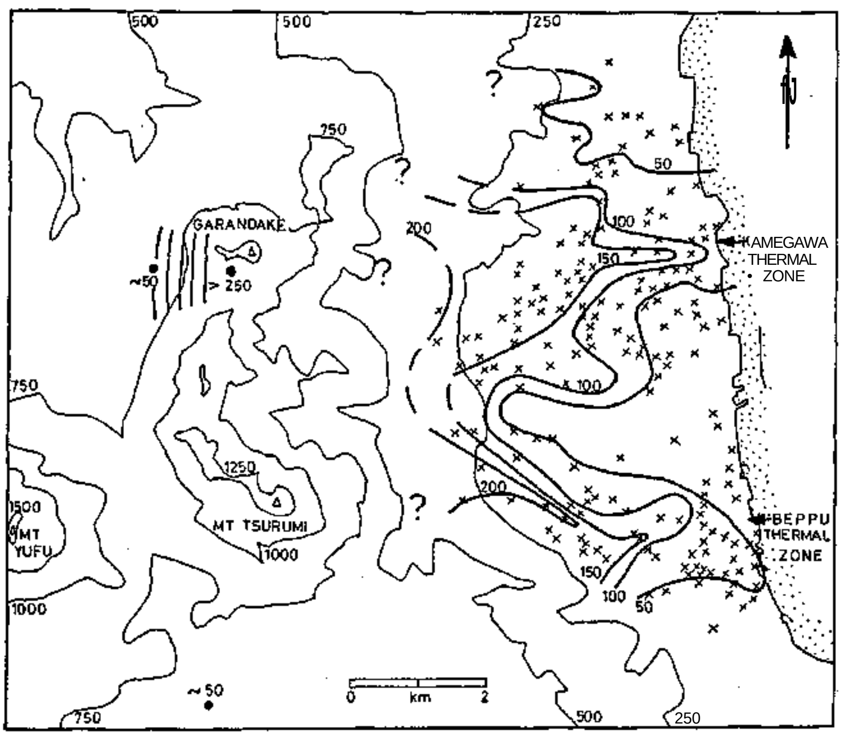

Figure 2: Isotherms at 100 m below sea level inferred from bottomhole measurements reported in driller's logs. Crosses mark the data points.

CHLORIDE-ENTHALPY TRENDS

The Geophysical Research Station, Kyoto University, Beppu has collected a large amount of data on the chloride concentrations of well discharges, and the respective mass -flows of steam and water at the wellhead. The mass flows can be combined to give the discharge enthalpy, and the chloride concentrations can be adjusted for the steam fraction to give the chloride concentration of the total discharge. This therefore enables a chloride-enthalpy plot to be constructed, and possible fluid flow relationships to be investigated. Figure 5 shows the available data for wells of the Beppu geothermal system. The

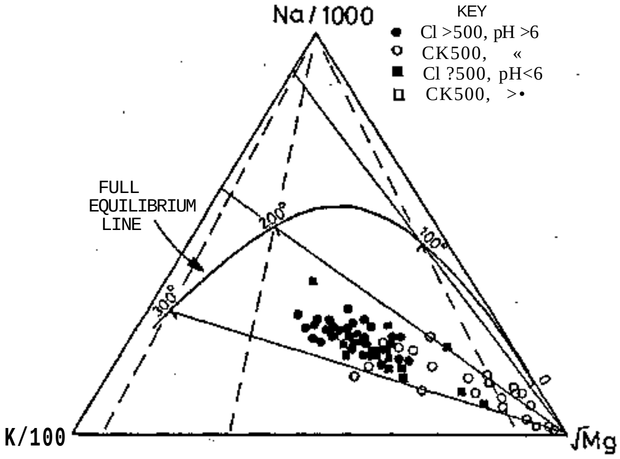

Figure 3: Application of the Na-K-Mg geothermometer to Beppu discharge waters (data for the period 1985-87). The data Imply a deep water temperautre of 250-300°C.

striking feature about Figure 5 is that the Beppu thermal zone fluids are concentrated in the low enthalpy - low chloride corner of the graph, whereas many of the Kamegawa thermal zone wells discharge a wide range of fluids suggestive of excess steam through to steam loss by boiling. This pattern is not simply due to the well distribution within each zone. Apart from the few Beppu thermal zone wells with low enthalpies and high chloride concentrations (due to seawater intrusion) the maximum chloride concentration in the higher enthalpy wells is 1300 mg/kg in the Beppu zona compared to close to 2000 mg/kg in the Kamegawa thermal zone. These differences need not indicate different fluid origins in the two thermal zones. Figure 5 shows that a single parent fluid is capable of devolving into the fluids found in each thermal zone.

The bottomhole temperature data and the geothermometry are consistent with a liquid parent temperature of 250 - 300 °*C, or* an enthalpy of 1100-1350 kJ/kg. With the constraints of steam loss or gain, or dilution, the data in Figure 5 requires a parent fluid to have a chloride concentration of at least 1400 mg/kg for this enthalpy range. If it is accepted that some dilution and some steam loss occurs in the deep upflow zone as the parent fluid rises towards the two outflow zones tapped by the wells, then the deep fluid could have a chloride concentration of at least 1600 mg/kg (shown in Fig.5). The essential difference between the fluids in the two zones appears to be that dilution dominates along the flowpath between the deep parent and the Beppu thermal zone, whereas boiling and steam loss is important in the Kamegawa thermal zone. This explains the significantly different chloride compositions of the 200 °C fluids in each zone.

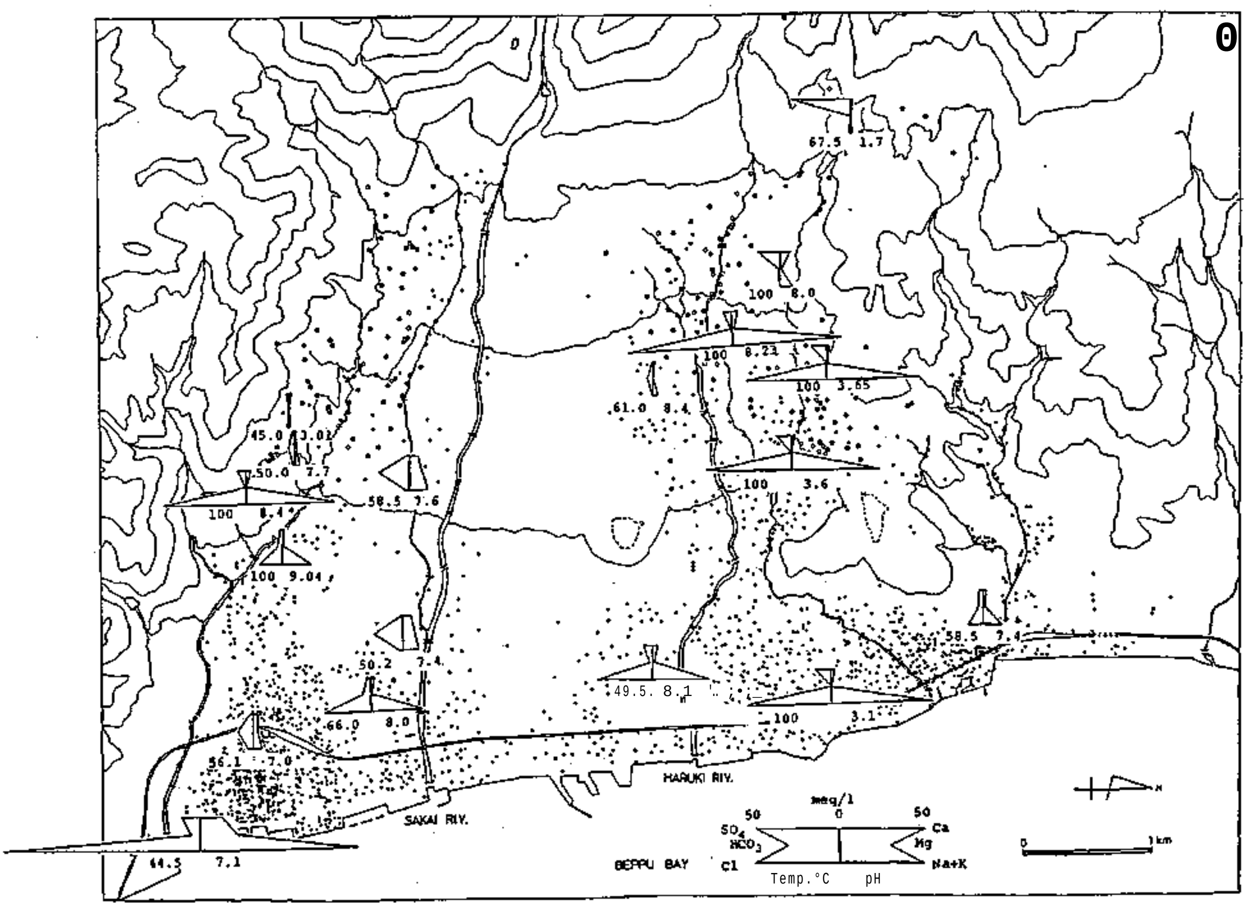

Figure 4: Hexa-plots of the major Ionic concentrations of discharge waters 1n different parts of the Beppu geothermal system.

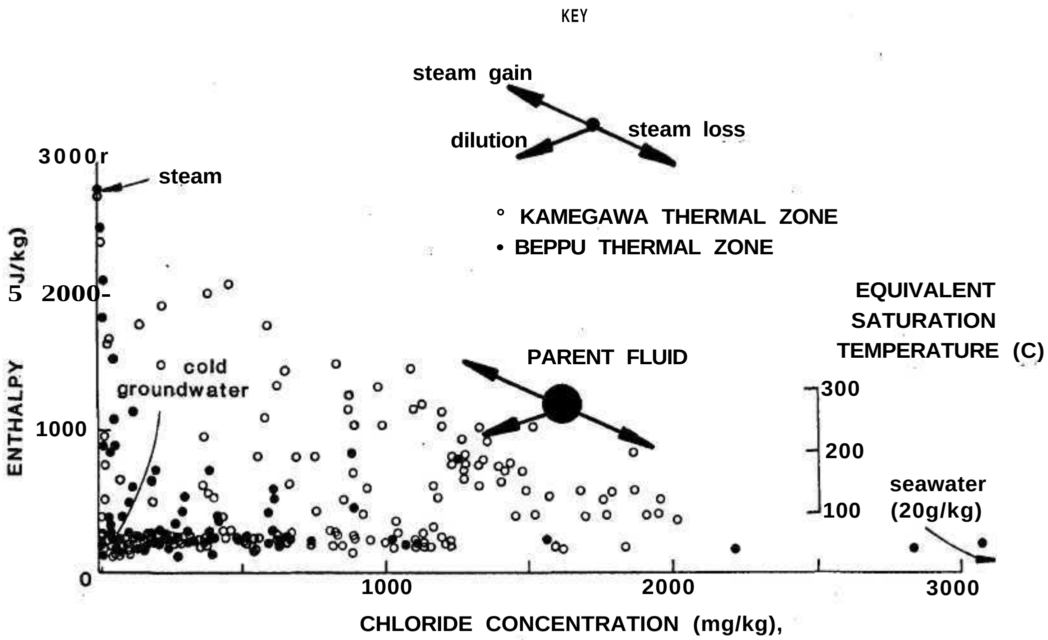

Figure 5: Chloride-Enthalpy plot of Beppu system discharge waters.

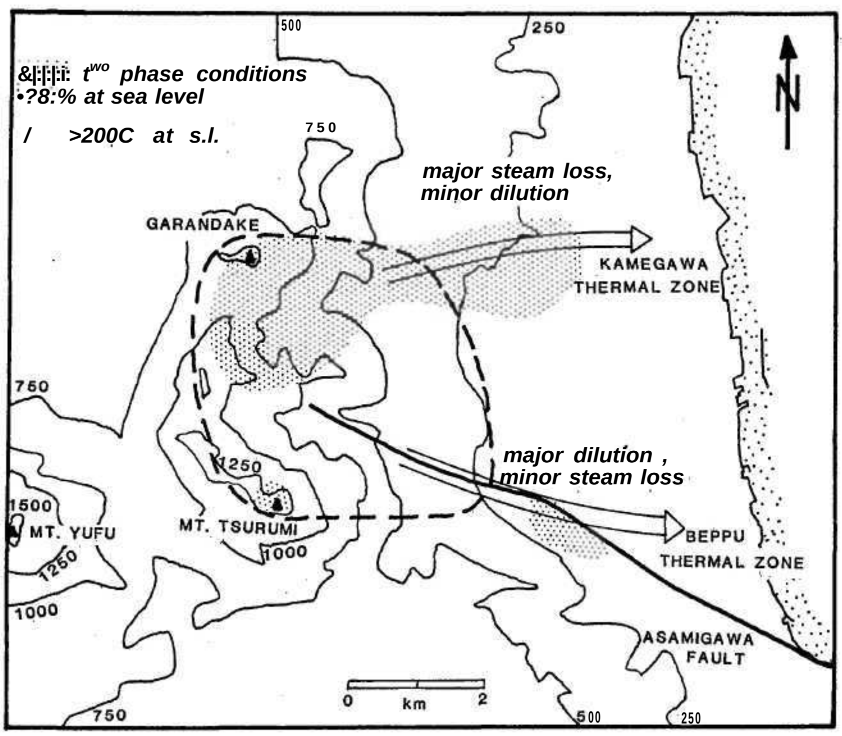

Figure 6: Identification of the main fluid flow processes in the Beppu geothermal system.

SUMMARY OF THE FLUID FLOW PROCESSES

The presence of two different fluid flow processes along the paths to the two out-flow zones of the Beppu geothermal system explains several other characteristics besides the difference in chloride concentrations. The intense acid alteration, the low pH fluids, the broad area of steam-heated thermal activity, and the abundance' of shallow, high enthalpy well discharges are consistent with boiling and steam loss from the fluid flowing to, and along the Kamegawa thermal zone. Here, steam zone(s) have formed at shallow depth within the upper flanks of Garandake. The relatively high gas content of the Beppu thermal zone on the other hand, may be due to the lack of boiling and dilution with grou.ndwater along this flow path (generally gas separates with the first steam).

Figure 6 shows the relationship between the extent of two-phase conditions at around sea level across the Beppu geothermal system, and the fluid flow processes discussed above. The two phase conditions *are* based on temperatures and pressures (water levels) in wells in the Beppu city area, and on the qualitative interpretation of the aeromagnetic anomaly pattern over Mts. Tsurumi, Yufu, and Garandake (Allis et al.,1988). The cones of Yufu and Tsurumi have prominent positive magnetic anomalies in contrast to Garandake which appears to be non-magnetic. The cone of Garandake appears to have had its magnetite destroyed by intense hydrothermal activity, such as that presently occurring beside the quarry near its summit. Here, acidic hydrothermal fluids have reduced the andesite to silica which is now being mined. The 600 m deep well here has two phase, liquid conditions at the bottom of the well (250 m.a.5.1.), so steam and gas are rising from below this elevation. The relatively high sulphidation state and acidic conditions that can occur in this situation cause magnetite to be replaced by pyrite or pyrrhotite.

The small fumarolic area at the top of Mt. Tsurumi indicates that that this volcano is also underlain by geothermal fluid. However in contrast to Garandake, the relatively magnetic andesite suggests the two phase zone feeding steam to the summit of Tsurumi is not extensive, and probably restricted to a pipe-like volume in care of the volcano.

The comparatively small thermal activity on Mt. Tsurumi, and the apparent lack of boiling along the flow path between the the deep Beppu fluids and the drilled part of the Beppu thermal zone, suggests higher fluid pressures beneath Tsurumi than beneath Garandake (i.e. at the same datum). Mt. Tsurumi is over 300 m higher so this could be contributing to increased pressure at depth due to infiltrating groundwaters. The western end of the Asamigawa Fault is deeply incised into the northern flanks of Mt Tsurumi, and forms a natural groundwater catchment which may also inhibit boiling at depth. The high productivity of wells drilled on the Asamigawa Fault in Beppu city indicates that this fault represents a high permeability path- for fluid flow along the Beppu thermal zone. No single fault seems to be controlling the Kamegawa thermal zone, however. The geothermal fluid appears to be flowing east from Garandake within a ridge of lavas. Between the two thermal zones is a 500 m thick, volcano-sedimentary fan deposit which probably has low vertical permeability, preventing flow to the coast.

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