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Comparative Analysis of the Structural Hydrogeological Conditions of the High Temperature Geothermal Reservoirs and Oil Deposit in Volcanic Areas

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ABSTRACT

An oil-bearing volcanogenic reservoir exists in West Siberia, hosted in Triassic age rocks (rhyolite tuffs) at a depth between 2.5 and 2.8 km and overlain by low-permeable clay-argillite formations. Reservoir temperatures range from 120 to 130 ^{o}C, and pressures from 290 to 310 bars. Integrated analysis of the geological and geophysical data shows circulation patterns, where upflow zones can be identified by positive temperature and pressure anomalies, while downflow zones lead to negative anomalies. These circulation patterns coincide with the former Triassic volcano vents, which are related to volcanic breccias.

Conceptual TOUGH-modeling was used to verify the possibility of oil deposit accumulation in a clay-overlain Triassic rhyolite tuff reservoir fed by oil-bearing upflows from buried volcanic vents. The first approach was 3D numerical model of the reservoir covering 10 x 8 x 3 km^3 and represented by a rectangular 10 x 8 x 30 grid. Inverse iTOUGH2-EOS1-modeling was used to estimate heat and mass flows and permeabilities. Next, direct T2VOC modeling used to reproduce oil distribution in the volcanogenic reservoir.

1. INTRODUCTION

The interest in oil volcanogenic reservoirs properties in addition to geothermal volcanogenic reservoirs properties arises from a recent finding of a large 250 mln year old rhyolite oil-bearing reservoir at temperatures up to 140 ^{o}C that is indeed in a geothermal volcanogenic reservoir. Extensive study of the Yucca Mountain tuff (12.5 mln years old) is presented in numerous publications (K. Pruess, 2001). One example of an oil bearing volcanogenic reservoir (35 mln years old) in Nevada is the Trap Springs oil field where 2.6 mln ton of oil was produced in 26 years (L. Anna, et al, 2007; D.French et al, 1997). This reservoir has non-welded tuff units, which would be productive in geothermal fields, switch to a caprock function in an oil field, while welded tuffs became fracture type oil reservoirs. Nevertheless, it is not clear what kind of channels transported oil from Permian systems source rock to the reservoir.

Studies of geothermal volcanogenic reservoir properties included in papers presented at WGC-2005 and in previous publications show that most of the high-temperature geothermal fields occur in hydrogeological structures of recent volcanic areas: 1. Basins of the Quaternary stratovolcanoes and shield volcanoes (15% of the world geothermal electricity production); 2. Contact zones of the Quaternary intrusions and dyke swarms hosted in Neogene-Quaternary volcanogenic basins (19%); 3. Artesian volcanogenic basins of the Neogene-Quaternary age (8%); 4. Contact zones of the Quaternary intrusions hosted in sedimentary basins (48%); and 5. Fault systems in basement rocks (10%).

Hydrothermal reservoirs in the Neogene-Quaternary volcanogenic formations include: 1. Single Fault or Multiple Faults Systems (Ogiri, Hatchubaru, Sumikawa, Okuadzu, Mutnovsky (Dachny), Momotombo, Lihir, Nevada Basins and Ranges); 2. Semi-permeable Faults (Dykes) (Mac-Ban (Bulalo), Tiwi); 3. Intrusions External Contact Zones (Matsukawa, Kakkonda, Uenotai, Fushime, Tongonan, Palinpinon, Krafla, Svartsengi, Nesjavellir, Hellisheidi); 4. Volcano Conduit Zones (Hatchijo-Jima, Darajat); 5. Unwelded Tuffs and Lavas Stratigraphic Contact Zones (Yellowstone, Los-Azufres, Ahuachapan, Miravalles, El-Tatio, Olkaria, Oguni, Takigami, Wairakei, Casa-Diablo, Pauzhetsky); and 6. Lava Formations (Kamojang).

The examples of the Pauzhetsky field (Kiryukhin et al, 2008) and Mutnovsky field (Kiryukhin et al, 2005, 2009) show that high-temperature upflows and recharge downflows coincide with faults or channels, which are also main conduits for magma extrusions and volcanoes (see Figures 1 and 2). This is probably a typical case for many geothermal fields.

Geothermal field exploration and modeling experience (especially numerical methods used for upflow zones identification and characterization) may apply to the oil-bearing volcanogenic Rogozhnikovsky reservoir in West Siberia, hosted in Triassic age rocks, which also shows multiple single faults and deep roots (Kiryukhin et al., 2008) (Figure 3).

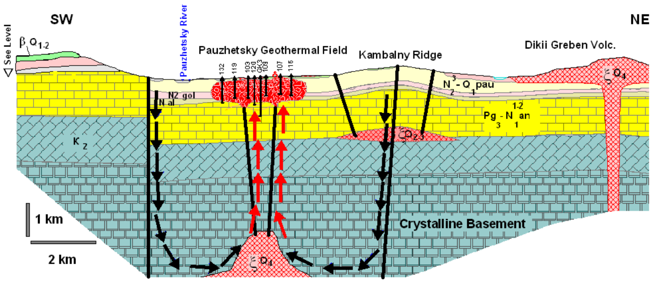

Figure 1: Conceptual hydrogeological model of the Pauzhetsky geothermal system (Kiryukhin et al, 2008). Lithologic units: K_2 – metamorphic basement, Pg_3-N_1^{1-2} an - Miocene sandstones, N al – Neogene andesite tuffs and lavas, N_2 gol - Golyginsky Layer, N_2^3-Q_1pau – Pauzhetka Tuff, βQ_{1-2}-andesites, ξQ_{2-3}, ξQ_4 – Dacite Extrusive Complex. Black arrows: cold-water (meteoric) recharge; red arrows: ascent of heated fluids; black lines: faults; short vertical black lines: geothermal wells

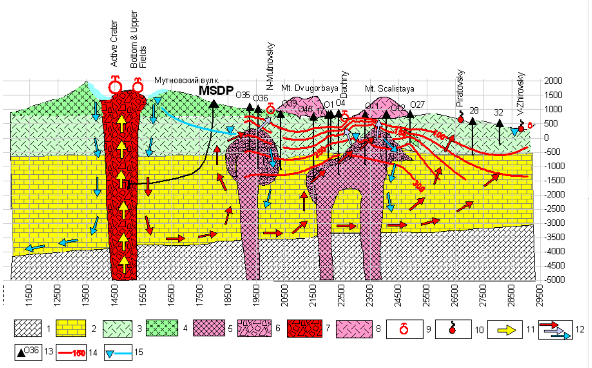

Figure 2: Conceptual model of Mutnovsky volcano - hydrothermal system: 1 – crystalline basement, 2 – Cretaceous basement and Neogene sandstones, 3- Neogene volcanogenic-sedimentary rocks, 4 – Mutnovsky stratovolcano (Q_3-Q_4), 5 – diorite intrusions, 6 – diorite intrusion contact zone, 7 – Mutnovsky volcano magma fed system, 8- rhyolite and dacite extrusions (Q_3-Q_4), 9- fumarole fields, 10 – hot springs, 11- magma and magmatic fluids, 12 – hydrothermal fluids, 13 – geothermal wells, 14 – temperature distributions, 15 – water level surface in reservoir. MSDP – proposed position of Mutnovsky Scientific Drilling Well

2. INPUT DATA FOR OIL DEPOSIT NUMERICAL MODEL

2.1 Geological Setting

Triassic volcanism in the Rogozhnikovsky area took place 242-258 mln. years ago (U-Pb dating, T.A. Korovina, 2008, pers. com.). Adjacent Pre-Jurassic rhyolites units, penetrated by wells below 2.5 km, cover a vast area around 500 x 250 km^2 (Bochkarev et al, 2008), which indicates either significant arc volcanism or intra-plate rifting conditions at that time. As a result of this geologic history, arc and rift fracture systems maintain active fluid circulation in the West Siberia basin, which causes significant vertical disturbance of brine concentration (heavy brines upflows and diluted fluids zones), thermal anomalies, and fluid pressure anomalies (low and over hydrostatic pressure zone; Matusevich et al, 2005).

An oil-bearing volcanogenic reservoir exists in West Siberia. It is hosted in Triassic age rocks (rhyolite tuffs) at a depth of 2.5 - 2.8 km and is overlain by low permeability clay-argillite formations. Reservoir temperatures range 120-130 ^oC and pressures range 290-310 bars.

Integrated analysis of geological and geophysical data shows circulation patterns. Upflow zones are clearly identified by temperature and pressure positive anomalies, and downflows are identified by negative anomalies. These circulation patterns do not clearly fit the fracture structure inferred from 3D seismotomography data (Fig. 3) and more closely coincide with the former Triassic volcanoes vents, which were detected by volcanic breccias penetrated by drill holes (Fig.4).

2.2 Thermal Properties

The heat properties of reservoir rocks were estimated based on experiments with cylindrical rock samples of 50 mm diameter and 50 mm height (Kiryukhin, 2009). The laboratory experiment setup includes a heat source (12 W) at the bottom of the cylindrical sample, a zond type temperature logger installed in a hole with a 2.4 mm diameter that is 10 mm from the top of the thermally insulated sample. A temperature logger was employed to register transient temperature changes (accuracy of measurements: 0.1^{o}C). All measurements took place in an underground facility with stable temperature conditions after 24 hr of delay time to reach constant initial conditions in the sample. Observational data include transient temperature records at 10 sec intervals during the first 5 min after the heat source was engaged.

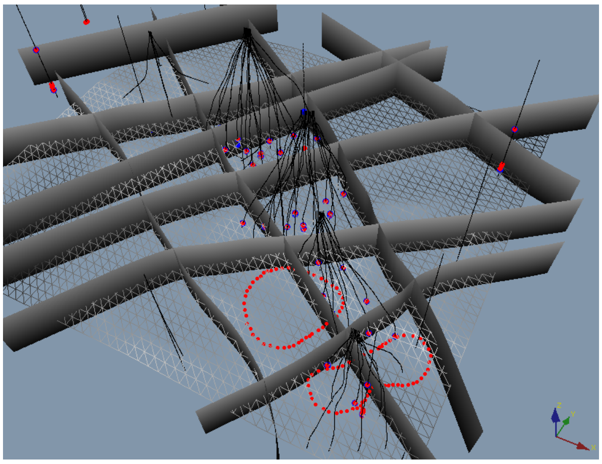

Figure 3: 3D view of Rogozhnikovsky (from Kiryukhin et al, 2008). Fractures inferred from seismo tomography data, red dotted lines – geoisotherms 120^{o}C at -2500 m.a.s.l., production zones – circles (oil – red, water – blue, oil above 25%+water – red with blue). Grid – roof of the Triassic volcanogenic reservoir

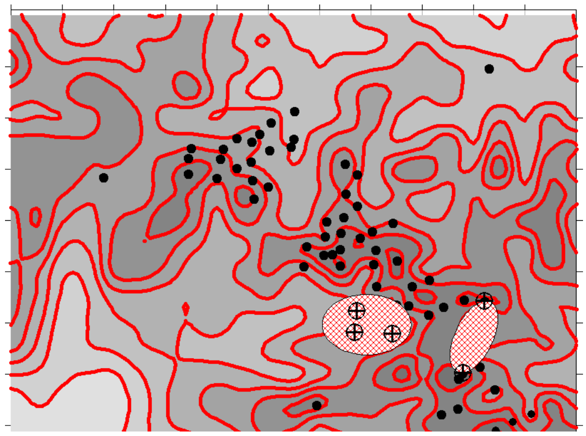

Figure 4: Surface of the volcanogenic unit (filled color, 50 m interval contours, darker at higher elevations), suggested volcanic vents shown by crossed hatched areas, wells – filled circles, wells penetrated breccias shown by crosses in circles. Grid size – 1 km

Grain density, porosity and permeability were assigned as known petrophysical parameters. Since 99% of the pore volume in the rock samples were occupied by air, the iTOUGH2-EOS-3 (S. Finsterle, 1999) module for water and air was used. A linear function was used for the heat conductivity, λ, as a function of water saturation S_w, i.e. $\lambda = \lambda_r + (\lambda_w - \lambda_r) S_w$, where λ_w is the heat conductivity of the wet rock, and λ_r is the heat conductivity of the dry rock. The measured transient calibration data were compared to the calculated temperature at the zond hole center. Model parameters to be estimated include heat conductivity (dry)

λ_r, specific heat C_r, initial rock sample temperature T_0 and heat source rate W. Initial temperature T_0 and heating rate W were added to the parameter list because, although measured during the experiment, small variations in T_0 and W have a large impact on the predicted temperatures. A four-parameter inversion shows acceptable correlations between the estimated parameters, which allows us to get sufficiently accurate estimates of heat conductivity (dry) (standard deviation: 0.1 W/m ^oC) and specific heat (standard deviation: 20 kJ/kg ^oC).

Based on inversion of 38 laboratory experiments on rock samples from a well that penetrated the volcanogenic reservoir at a depth between 2580 and 2795 m, an average value of heat conductivity (dry) of 1.44 W/m ^oC, and an average specific heat of 850 kJ/kg ^oC was obtained. Accordingly to Rautman function the saturated rock has a thermal conductivity of about 1.88 W/m ^oC (1.44 dry rock + 0.44 water contribution).

2.3 Hydraulic Properties

The volcanogenic reservoir is characterized by double-porosity properties that were identified based on the Fracture Micro Images (FMI) study. The average vertical fracture spacing was FS=26 m, fracture aperture 0.17-0.5 mm (average 0.3 mm), and fracture volume fraction FV= 3.17×10^{-5}. Corresponding fracture permeability ranges from 0.23 to 1.59 D (assuming a parallel plate model), while matrix permeability is 1.4 mD.

Laboratory study of the relative permeabilities of volcanogenic reservoir rock samples suggests that the van Genuchten model is appropriate for the water phase (0.2 – 0.5 residual water saturation), whereas a Corey's model can be conveniently used to describe the oil relative permeability (0.3 – 0.4 residual oil saturation). A laboratory study of the capillary pressures of volcanogenic reservoir rock samples suggests that the van Genuchten model (λ=0.4438, Slr=0.22, 1/P0=1.50E-05, Pmax=50 atm) can reasonably match the experimental data (water/air). Note that West Siberian reservoirs are generally characterized by hydrophobic properties, caused by high feldspar mineral fractions (Matusevich et al., 2005). This means that positive oil/water capillary pressures may keep the reservoir oil-wet. According to Matusevich et al. (2005) positive capillary pressures may reach 5.6 bars under some reservoir conditions, reducing the efficiency of oil recovery from the matrix by water flooding.

Inverse iTOUGH2-EOS10 modeling applied to test the problem of 2-wells injection/production yields the following range of estimated parameters: initial oil saturation 0.74, reservoir compressibility 2.3 10-9 Па-1, and productivity index 2.4 10-14 – 5.1 10-14 м3. Modeling study shows that reservoir double porosity behavior is more significant at matrix permeability less than one hundreds of mD under oil-wet conditions.

3. NUMERICAL MODELING OF OIL DEPOSIT FORMATION IN VOLCANOGENIC ROCKS

3.1 Model Setup

TOUGH-based numerical modeling (K. Pruess, 1999) was used to understand oil formation and distribution in reservoir. The first approach was a 3D numerical model of the reservoir that covered 10 x 8 x 3 km^3 and was represented by rectangular 10 x 8 x 30 grid. This model covers area shown on Fig. 4.

The upper layer of the model (#30) was assigned at a fixed state condition (10 bars, 5 ^oC), which corresponds to conditions approximately 100 m below earth surface, where annual pressures and temperatures are constant. The bottom layer of the model (#1) include sources (potential upflow zones, where positive mass flow rate and enthalpy are assigned), sinks (potential downflow zones, where negative mass flow rates are assigned), and conductive heat flow sources in all elements of the bottom layer.

Regional and local lithologic characteristics used as input data for numerical model are summarized in Table 1. These data were obtain from core studies and correspond to matrix properties of reservoirs. Model zonation is illustrated by Table 2.

Table 1. Regional lithologic characteristics: ρ - grain density, ϕ - porosity, k - permeability, λ - heat conductivity, SH – specific heat.

Geological index	ρ kg/m^3	ϕ	k mD	λ W/m^{o}C	SH кJ/kg^{o}C
K_2-Q caprock	2700	0.35	0.1	1.1	800
K_{1-2} aquifer J-K_1 caprock J aquifer	2700	0.20	0.19	1.2	900
Tr volcanogenic reservoir	2620	0.16	1.0	1.8	1000
Basement	2800	0.02	0.1	2.1	1000

Table 2. Model Zonation.

Geological index	Lithology	Model layers	Elevations m.a.s.l.	Domain name
K_2-Q caprock	aleurite, clays	26-40	-1450, -50	K2Q_1
K_{1-2} aquifer J-K_1 caprock J aquifer	Sand-aleurite,	14-26	-2650, -1450	JK__1
Tr volcanogenic aquifer	Lavas, clastolavas, tuffs and breccias	11-16	-2950, -2450	TR___
Basement		1-10	-3950, -2650	BASE1

3.2 Inverse iTOUGH2-EOS1-Modeling

Inverse iTOUGH2-EOS1-modeling (S. Finsterle, 1999) was used to estimate heat and mass flows and permeabilities (base conductive heat flow, permeabilities of J-K_1 and K_2-Q units, upflow rate and enthalpy, and downflow rate). Model calibration was based on 41 temperature and 20 pressure calibration points. A natural-state run was performed for 10^6 years. Modeled and measured data matched relatively well, with a mean temperature deviation (bias) of -0.3 ^oC, a temperature standard deviation of 5.6 oC, a mean pressure deviation of -0.03 bars, and a pressure standard deviation of 8.9 bars (3% of absolute value). The uncertainty of some parameter estimates is rather high, most likely due to over–

parameterization that leads to strong correlations, specifically between mass flows and the permeability of the K2-Q unit). The best estimate values are: 50.2 mW/m2 for base conductive heat flow; 0.19 mD and 0.0011 mD for thepermeabilities of the J-K1 and K2-Q units, respectively; 3.6 kg/s with enthalpy of 558 kJ/kg for total upflow rate; and 3.6 kg/s for downflow rate (A.V. Kiryukhin, 2009).

Figure 5 shows corresponding pressure and temperature distributions at -2550 m.a.s.l. Upflow and downflow in the model are the same, indicating that a circulation pattern exists in the basement of volcanogenic reservoir, in spite of recharge boundaries specified on the top of reservoir.

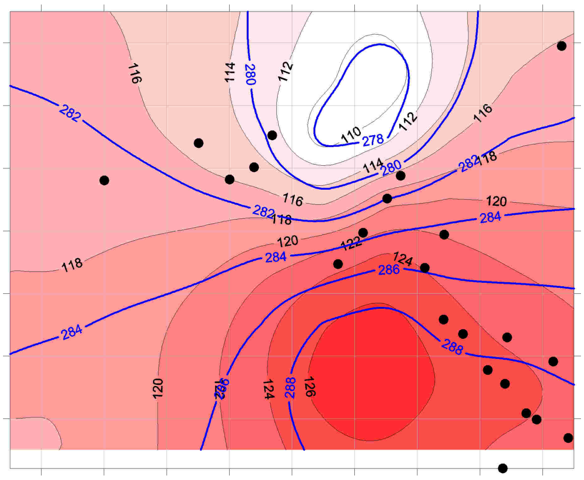

Figure 5: iTOUGH2-eos1 natural state modeling: temperature and pressure distributions at -2550 m.a.s.l. Grid size – 1 km

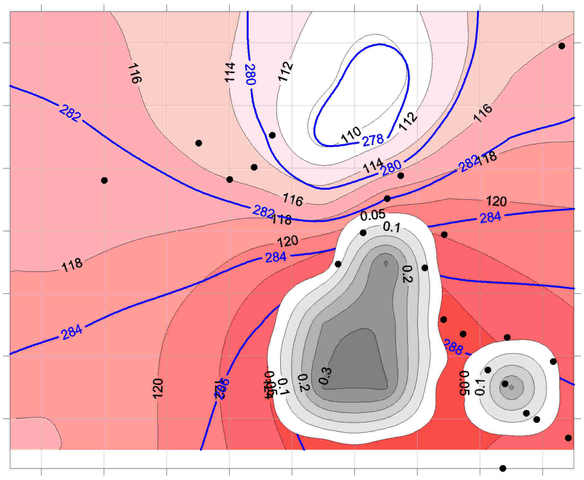

Figure 6: TOUGH2-eos10 natural state modeling: oil phase saturation, temperature and pressure distributions at -2550 m.a.s.l. Grid size – 1 km

3.2 T2VOC (direct iTOUGH2-EOS10)–Modeling

T2VOC (direct iTOUGH2-EOS10; R. Falat et al, 1995, S. Finsterle, 1999) –modeling was used to reproduce oil distribution in the volcanogenic reservoir, based on initial conditions obtained by iTOUGH2-EOS1-modeling performed before. The following scenario was used: 75.6 10^9 kg (0.24 kg/s) of oil injected into reservoir through the base upflow zones over 10000 years following 90000 years of single water upflow conditions. Resulting oil phase saturations are shown in Fig. 6. Hence, TOUGH-modeling shows the possibility of oil deposit accumulation in a clay-overlain Triassic rhyolite tuff reservoir fed by oil bearing upflows from buried volcanic vents (Fig. 7).

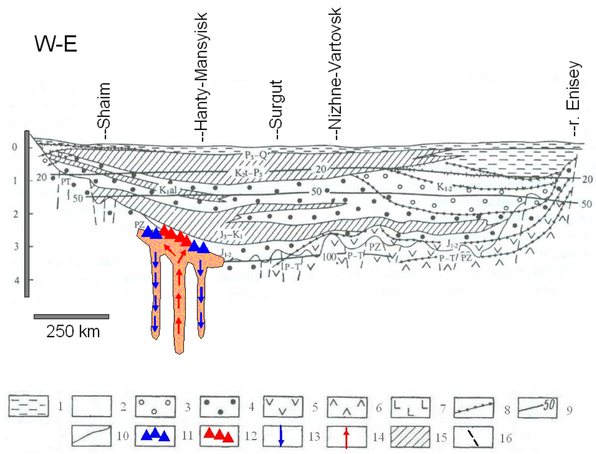

Figure 7: Cross section of West Siberian basin (from V.A. Kiryukhin, 2005) with added schematic indication of Triassic volcanogenic reservoir and possible circulation patterns along former volcanoe vents. Legend: 1 – 7 hydrogeochemical zonation: mineralization < 1 g/l (1), 1-3 g/l (2), 3-10 g/l (3), 10-35 g/l (4), 35-70 g/l (5), 70-150 g/l (6), 150-375 g/l (7); 8 – hydrogeochemical zone boundaries; 9 – geoisotherms, °C; 10- lithological boundaries; 11 - water filled volcanogenic reservoir;12 – oil filled volcanogenic reservoir, 13 – separated water downflow channels; 14 – oil bearing ascending fluid channels; 15 – clay caprock units; 16 – faults

4. FUTURE STUDY

A more detailed model approach for natural state and different exploitation scenarios is needed. This study should include Voronoi grid generation, taking into account the entire field temperature and pressure distributions, double-porosity properties, spatial distributions of reservoir parameters (such as matrix porosity, permeability, initial oil saturations, potential oil-water upflow zones) as confirmed by extensive geophysics well logging, seismo tomography and FMI, and as extensive core petrophysical studies. Oil production and water production history matching is also planned. It would be necessary to consider in a more rigorous way the effects of brine properties that are functions of salt concentration (e.g. density and viscosity). Future drilling locations and methods to improve the efficiency of oil recovery from oil-wet volcanogenic reservoir conditions remain the primary challenge.

CONCLUSIONS

1. Based on analyses of hydrothermal reservoirs in recent volcanic areas, a conceptual model of oil reservoir formation in old volcanogenic formations was hypothesized. It was assumed that these reservoirs may use former volcanoes vents buried under sedimentary basins as channels of ascending oil-bearing fluids.

2. Conceptual iTOUGH2-EOS1 natural-state modeling based on measured pressure-temperature calibration data is an effective tool to verify deep seated circulated mass flow conditions, base conductive heat flow and permeabilities, nevertheless, just three of six estimated parameters are independent enough for accurate estimations. The best estimates obtained were a base conductive heat flow of 50.2

mW/m^2; J-K_1 and K_2-Q permeabilities of 0.19 mD and 0.0011 mD, respectively; total upflow rate of 3.6 kg/s with an enthalpy of 558 kJ/kg; and a downflow rate of 3.6 kg/s was assumed to be one of possibilities.

3. Conceptual T2VOC (direct iTOUGH2-EOS10) modeling was used to demonstrate the possibility that oil deposits could accumulate in clay-overlain Triassic volcanogenic reservoirs fed by oil-bearing upflows from buried volcanic vents.

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