The Generation of High-Enthalpy Geothermal in a Nonvolcanic Environment, a Case Study of Yangbajing Geothermal Fields, Qinghai-Tibet Plateau, China

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ABSTRACT
Among global high-enthalpy geothermal resources, only geothermal fields within Tibet are located in a non-volcanic environment. Results of the PTt (pressure-temperature-time) trajectory calculation of the Plateau uplifting gave a comparatively satisfactory explanation for the formation and for the depth of burial of high-enthalpy resources—the reason why an volcanic environment is not formed.

The method of PTt trajectory reconstruction used in the study of metamorphic rocks can be adopted for study of thermal evolution of young orogenic belts. For lack of petrographic PT data recording the influence of uplifting in Qinghai-Tibet plateau, we brought such data from the Caledonides orogenic belt of North Europe for the calculation. The results show that any double-layered block can make the earth crust “heating” and originate high-enthalpy geothermal activities near the earth surface, if only it uplifts at a high speed. The calculation of the Qinghai-Tibet plateau uplifting model showed that along with the increase of uplifting speed, the temperature of the earth crust increases and the depth to high-temperature front increases.

A new type of high-enthalpy geothermic—the uplifting – thick crust type—is being put forward.

INTRODUCTION
In 1987 the geothermal fluid with temperature of 202ºC was exposed by drill holes in Yangyi, Tibet. In 1993, it was found in Yangbajing, located at 45 km from Yangyi that at a depth of 2000m in the hole, the temperature reached 262ºC. The existence at shallow depth of such a high-enthalpy fluid on the Qinghai-Tibet plateau is entirely beyond expectations of experts at home and abroad. In order to find out more high-enthalpy resources, it is necessary for us to make a theoretically new interpretation.

At present two methods to predict enthalpy levels of geothermal resources are used. One is correlation, to compare with well-known geothermal fields of analogous geology in the world, then a regional qualitative prediction of high or medium or low enthalpy level can be obtained. The other is quantitative prediction, made on the basis of geophysical and geochemical data, such as terrestrial heat flow, burial depth of Curie interface and chemical geothermometer. It is difficulty to make qualitative prediction of geothermal enthalpy by these methods in Qinghai-Tibet, because of the uniqueness of the geological conditions.

Having demonstrated the particularity of high-enthalpy resources of Tibet in the world, the authors studied their formation by means of mathematical modeling.

2. HIGH-ENTHALPY GEOTHERMAL RESOURCES OF QINGHAI-TIBET PLATEAU: A NEW GEOLOGICAL GENETIC TYPE

Geothermal resources can be regarded as “Heat Mining” and the magnitude of fluid temperature as the grade of ore. We classify the big and the super-big heat-mining in the world according to their geological types and grades of ore. The former is based mainly on the arrangement in space of the magma system — which serves as the thermal source, and the hydrological system — which serves as the heat transfer medium and carrier. The latter is based mainly on the reservoir temperature. A brief account is given in Table 1. The temperature magnitude of high-enthalpy geothermal fluid has been summed up as follows:

—The highest record on the ocean floor: metallic ferrous fluid of 350ºC flowed from out “black chimneys” on the mid-ocean ridge in East Pacific Ocean, overheated water with temperature of 400ºC, yielded from beneath the sea floor 300 miles to the west of Seattle, United States;

—On the continent, the highest temperature was found in the geothermal field at Cerro Prieto, Mexico, which is a segment of continuation of the mid-ocean ridge of the East Pacific Ocean onto the continent. The TDS of geothermal fluid is 10-20g/l with a temperature over 350ºC (in some references 370ºC);

—The reservoir temperature of large steam fields (includes dry steam fields) ranges from 180ºC to 270ºC including many well-known in the world;

—For many high-temperature geothermal fields in the world located close to active volcanoes, the temperature of geothermal reservoir is in the range of 200 to 400ºC;

—In some geothermal fields, where drill holes reached into liquid magma, for example, at Krafaila, Iceland, the temperature of the reservoir is in the range of 300 to 350ºC; at Kilauea , Hawaii, United States, temperature reached 340 to 358ºC (maximum in the drill hole of 363ºC).

An empirical conclusion can be drawn by means of the inductive method: for hydrothermal systems on the continent above a depth of 4 km, the maximum temperature of the reservoir roughly ranges between 300-370ºC. This is the highest temperature that the hydrothermal system with near-surface magma as its heat source can reach, and it already reached or approached close to the limiting temperature of the liquid state — the critical point of pure
water is 374.1°C and that of aqueous solution containing \( \text{CO}_2 \) and \( \text{NaCl} \) — approximately 400°C.

These high-enthalpy resources, without exception, have the geological background of active volcanos. Rybach (1981) summarized them into four genetic types in the sense of plate tectonics: (1) spreading-ridge of plate-edge, (2) convergence belt, (3) continental rift and (4) thermal plate tectonics: (1) spreading-ridge of plate-edge, (2) continental rift, (3) thermal plate tectonics, (4) oceanic island. Rybach (1981) summarized them into four types in the sense of geological background of active volcanos. These high-enthalpy resources, without exception, have the geological background of active volcanos. Rybach (1981) summarized them into four types in the sense of geological background of active volcanos. These high-enthalpy resources, without exception, have the geological background of active volcanos. Rybach (1981) summarized them into four types in the sense of geological background of active volcanos. These high-enthalpy resources, without exception, have the geological background of active volcanos. Rybach (1981) summarized them into four types in the sense of geological background of active volcanos. These high-enthalpy resources, without exception, have the geological background of active volcanos. Rybach (1981) summarized them into four types in the sense of geological background of active volcanos.

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Both on satellite gravity and MAGSAR images, Qinghai-Tibet plateau is displayed as a unified and complete block of continental lithosphere. However, according to surficial geophysical prospecting, the plateau showed a nature of being divided into blocks. Some people considered that it consisted of five terrains, which are pieced together. According to the results of the China-Britain cooperating investigation (1985) it was divided into four terrains. These comparatively stable terrains were “welded” into a whole by relatively active suture belts in the Late Cretaceous to Tertiary.

The results of ultra-deep prospecting by subvertical seismic reflection technique -- a cooperative project between China and United States -- showed that near the main Himalayan ridge the Moho depth reaches at most 75 km. The extremely thick earth crust of the Himalayas has a double-layer structure. From the depth of 28 km at the Himalayan mountains to the depth of 40 km under Shixian located to the north, there exists the main fault of the Himalayas which extends from south to north over 100 km long, where the Indian Plate subducted under the Tibet block (Zhou Wen-jin, China Geology and Mineral Resources News, 01/10/1994).

The average thickness of the earth crust in Qinghai-Tibet plateau is 70-80 km, with the maximal thickness along the valley of the Yaluzangbu river. On the basis of telluric electromagnetic sounding and seismic surface waves, the thickness of the lithosphere is respectively 120-150 km and 90-120 km. On the whole, it is thicker to the north and thinner to the south, the maximum thickness is at Qiang-tang terrain and is about 200 km.

The plateau has two low-velocity, low resistivity layers. The “upper layer” has a thickness of 10-13 km and a burial depth of 10-30 km, to the south it gradually rises, and in the north part of Tibet the layer thinned to 5 km and became horizontal. The upper low-velocity and low-resistivity layer is a detachment interface structurally, above which is the upper crust composed of sal, the thrusts led to the formation of a series of nape structures and resulted in thinning of the upper crust. The low-velocity and low-resistivity layer in the lower crust is buried at a depth of 50-60 km, the thickness of the layer is 4-12 km to the south at high Himalaya and to the north at Naqu of north Tibet, the low-velocity and low-resistivity layer gradually disappeared. The sima as a lower crust caused overlap and thickening by plastic folding or ductile shearing. In an area to the north of Nianqingtanggula mountain, at a depth between 50-60 km and 70-80 km, there existed a crust-mantle transitional layer (i.e. anomalous mantle), which resulted from upsurging of mantle materials and interaction between it and crust substances.

Geological and paleomagnetic data indicate that since the Late Eocene the earth crust of plateau is reduced from 2400 km to 1200 km nowadays, at the same time, the thickness has nearly doubled. The discovery of Hipparion and Early Pliocene, the earth crust shortened and thickened on a large scale, the plateau was...
rising gradually, the upper mantle subsided at a large scale, forming the wide and deep mountain root of the plateau;

—Second stage, from Early Pleistocene until now, with slow down of drift velocity of the plateau in its entirety and decrease of drift velocity difference among microplates; there appeared stress relaxation, and squeezing action diminished greatly. Under the action of the mountain root, there appeared intensive balancing regulation leading to high speed uplift of the plateau.

The total uplift at the first stage is nearly 1.5 km, and at the second stage 3.5 km. At this stage the plateau surface, which we see nowadays with an average elevation of 4500m above sea-level, took shape and is higher than the average continental surface of the earth by 2-3 km.

According to the data of geographical department, Lanzhou University (1994) the yearly uplift of the plateau was: 0.78 million years before < 1.3 mm; 0.2 million years B.P. 4.8 mm; 0.15 million years B.P. 5.6 mm; 0.12 million years B.P. 6.1 mm; 50 thousand years B.P. 7.9 mm; since 18 thousand years B.P. 9.2 mm. According to the data of Geographical Institute, Chinese Academy of Science, the yearly average uplift on the north slope of Kunlun mountain is 8 mm; on the Himalayan mountain—10 mm; on the peak of Qomolangma ~30 mm (China Geology and Mineral Resources News, 27/07/1994).

The upper, medium and lower three parts of lithosphere of Qinghai-Tibet plateau as a whole, made coupled with each other as well as peculiar to each part response in the process of uplift. The uplift of Qinghai-Tibet plateau showed that the elevation of the plateau is a whole; by stages in time and speeding up at a later stage.

4. THE MATHEMATICAL MODELING METHOD OF THERMAL EFFECT OF THE UPLIFTING

From the viewpoint of formation of geothermal resources, the heat structure and thermal evolution of the crust is of great importance. On the one hand the earth crust is giving heat due to contained radioactive elements and on the other hand it is a medium through which the heat is transferred from the upper mantle upwards. In fact, 20-80% of terrestrial heat flow comes from the heat source produced in the earth crust, therefore after the geologists and geophysicists argued uplift and thickening of the crust in Qinghai-Tibet plateau, it is natural for geothermal experts to put forward a question as to what thermal effect is caused by the process of uplifting-thickening of the plateau crust itself?

Royden and Hodges(1984) have put forward a mathematical method for reconstruction of thermal history of orogenic belt taking Caledonides of Scandinavia as an example. This orogenic belt is an early Paleozoic subduction zone of A type, resulted from thrusting of the Baltic craton on the Greenland craton, followed by an uplift and simultaneous erosion. For the geological model the following restrictions are postulated: (1) uplifting velocity is equal to erosion velocity and they are both constant; (2) in the process of uplifting, the earth crust was thinning continuously while the thickness of the lithosphere was kept constant; (3) after the nape has taken its place, the upper block is thermal — from top to bottom the temperature increased linearly from 0°C to 800°C; the lower block is cold — the temperature on the top is 0°C and increases linearly downward to 1333°C at the bottom of lithosphere; (4) the radioactive heat production of the crust and the temperature of the lithosphere bottom are both kept constant. In this way, as long as the burial depth and temperature at some point in the crust which is formed at any moment during uplift is known (they can be derived from petrographic study of rock samples), the steady-state distribution of temperature in the profile of the lithosphere at any moment and any speed of uplift, and the curve about steady-state temperature versus depth in lithosphere can be calculated according to the following equations (1), (2). The meaning of symbols in equations is given in Table 2.

\[
T(z,t)=T_R(z,t)+T_{m}[1-e^{-2Rz/L}]/(1-e^{-2R})+T_m\sum_{n}C_n\left[-e^{-R/L}\sin(n\pi z/L)+T(0)-T_m\right]e^{Rz/L}\sin(n\pi z/L)dz \tag{1}
\]

Where \( T_c = (2L/T_m)^{1/4} \) and \( (T(Z,0)-T_m) \)

\[
-T_m[1-e^{-2Rz/L}]/(1-e^{-2R})\right)e^{Rz/L}\sin(n\pi z/L)dz \tag{2}
\]

Equation (1) describes thermal conductivity in a moving media, including two types of heat transfer—conduction and convection. The heat from thermal effect in an isovelocity uplifting process of a double-layer block described by the equation is composed of three parts: radioactive heat production as a function of time and depth (the value is equal to zero on the top and bottom of the lithosphere). The heat contributed by the asthenosphere to the lithosphere is divided into two parts: one part is time-independent and only attenuates exponentially with depth; the other part attenuates exponentially with time. This part of heat is calculated by means of the accumulation method, which can be done according to the duration of uplift and arbitrarily selecting the number n of times of heat-transfer. For the uplifting process of shorter duration, a bigger value must be taken for n in order not to lose the heat transferred by short wavelength.

Applying this method to the Qinghai-Tibet plateau, we have made some conceptual modifications to suit the method for the local geology and for data known at Qinghai-Tibet plateau (Figure1). Suppose the uplifting velocity of the crust equals negative, this signifies that due to the constant thickness of the lithosphere, the uplift of the block is same as the interface between the two layers of the binary structure that moves to the bottom of lithosphere, and along with it the thickness of upper block increases. As the thickness of upper block for the model of original state, we take roughly the middle value (30 km) of thickness of upper crust which is discussed in the previous section. The upper crust of 30 km in thickness constitutes the upper block of the double-layer model. This means that in the Qinghai-Tibet plateau, pre-Quaternary uplift stage at a “normal” speed has already ended, so to calculate the thermal effect of Quaternary uplift stage the uplift has to be of “extraordinary” speed. Because the calculated value of uplift duration in the mathematical model requires us to calculate the beginning from the original state of the geological model, we adopted four kinds of uplift duration—0.03, 0.1, 1 and 3Ma in order to model four periods: early, middle, late Pleistocene and Holocene of Quaternary. Because the uplifting velocity in the mathematical model is a constant over the calculated time span, the result calculated is only a rough approximation to the actual process of “accelerating uplift at late period”, although for various periods we took corresponding actual uplifting velocity. In other words, the calculated temperature structure of lithosphere at five time
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stages (including the original state) in the case of six uplifting velocities (Figure 2), are not at five geological periods (Pliocene to Holocene) in a strict sense.

5. DISCUSSION ON THE RESULTS OF MODELING

Analytical diagrams (Figure 3) can be made on the basis of the calculated results shown already in Figure 2. Figure 3a indicates the increased quantity of heat in the crust after uplift relative to that before uplift (original state). The relatively increased quantity of heat is calculated by determining the area enclosed by the ordinate axis and the segment with peak-form high-temperature in the upper part of each curve in Figure 2. Then, by taking the area of No.1 curve which stands for the original state before uplift as denominator and dividing it by the determined area for each curve, the “rate of relative increasing of heat” of crust for various duration and velocity are obtained.

Figure 3b shows the relationships between uplifting velocity, uplift duration, peak value of high-temperature front in crust and burial depth of the peak value. The latter two parameters are derived from the absissa and ordinate of turning points of the segment with peak-form high-temperature of curves in Figure 2.

Through mathematical modeling (Figures 2, 3) we brought to light the variation of temperature structure of the lithosphere caused by the speed uplift of plateau. This variation affected the formation of geothermal resources and regional geophysical fields related to the thermal field as well. The explanation of this is given below.

(1) Speed of uplifting-thickening of the crust in Qinghai-Tibet plateau itself can cause the crust “heating”. With the increase of uplifting velocity, the heat in the crust increases by about 1-20% higher than that before uplifting. As to the time effect of uplifting, the terrain of long duration can reach the same heat increase even at a smaller uplift velocity. Apart from the significance to the formation of geothermal resources, the increase of heat by way of crust uplifting also has significance in continental dynamics. Heat expansion and lightening of the tremendously thick crust is a response to the balance process in the lithosphere. One related fact is that the value which reflects accelerated uplift in the late period, may include some amount of heat expansion of the crust.

(2) “The accelerating uplift at late time” at Qinghai-Tibet plateau experienced, in the beginning, a certain period of regulation (it is expressed in Figure 3b as the discordance of No.2 curve compared with the other curves). Starting from the Miocene (No.3 and No.4 curves in Figure 3b are taken as representative), geotemperature increases with the faster velocity. Apart from the significance to the formation of geothermal resources, the increase of heat by way of crust uplifting also has significance in continental dynamics. Heat expansion and lightening of the tremendously thick crust is a response to the balance process in the lithosphere. One related fact is that the value which reflects accelerated uplift in the late period, may include some amount of heat expansion of the crust.

(3) After each tectonic event, the thermal field changes much slower than the regulation of the stress field due to the thermophysical characteristics of the lithosphere. The lithosphere of Qinghai-Tibet plateau recorded the thermal effect of every tectonic event. Figure 2 and Figure 3 indicate that the peak values of the heat-front at the early stage of uplifting are concentrated at a depth from 20 to 40 km, and at the late stage, 50-60 km. They are likely to correspond in position to two low-velocity and low-resistivity layers, existing in the upper and lower crust as mentioned in the conceptual model. It is well known that the Moho is determined on the basis of a sudden change of seismic P wave velocity in the lithosphere from low to high values (the peak value of the “low-temperature front” in Figure 2 is too low, which may result from excessively low postulated original temperature of the lower block in the mathematical model, but the low-temperature property and depth of the front are still tenable). The low-temperature front of the plateau lithosphere appears to be concentrated at a depth of 70-80 km, corresponding to the depth of the Moho. The coincidence between two is rational in explaining the geophysical properties, because the medium has low temperature, and therefore has great density and larger elasticity, giving an expression in high P wave velocity.

ACKNOWLEDGEMENT

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REFERENCES


Table 1: Geological types and reservoir temperature of geothermal systems with high-enthalpy level in the world

<table>
<thead>
<tr>
<th>Geologic type of geothermal systems</th>
<th>Reservoir temperature (°C)</th>
<th>Case histories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-oceanic ridge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea floor</td>
<td>350-400</td>
<td>Mid-ocean ridge (N.L.21) of East Pacific Ocean; ocean ridge Huan de Fuca near Oregon, USA</td>
</tr>
<tr>
<td>Continent</td>
<td>350-370</td>
<td>Cerro Prieto, Mexico; Krafka, Iceland</td>
</tr>
<tr>
<td>Continental volcanic environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of magma disturbance</td>
<td>300-360</td>
<td>Krafka, Iceland</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kilauea, USA</td>
</tr>
<tr>
<td>Active volcano area</td>
<td>200-400</td>
<td>BaoMan, Tongonan, Philippines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hatcho-hara, Japan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Da-Tun, Taiwan, China</td>
</tr>
<tr>
<td>Big steam field</td>
<td>180-270</td>
<td>Larderello, Monte Amiate, Italy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wairakei, New Zealand</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The Geysers, USA</td>
</tr>
<tr>
<td>Non volcanic environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uplift-thick crust type</td>
<td>200-260</td>
<td>Yangbajing and Yangyi, Tibet, China</td>
</tr>
</tbody>
</table>
### Table 2: Values and Symbols Used

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Initial depth to base of heat producing layer at t=0</td>
<td>38km, 30 for upper block, 8 for lower block</td>
</tr>
<tr>
<td>α</td>
<td>Thermal diffusivity</td>
<td>$1 \times 10^{-6}$ m$^2$/s</td>
</tr>
<tr>
<td>A(z+ut)</td>
<td>Heat production</td>
<td>Upper block 2.0 $\mu$ w/m$^2$ k, lower block 0.5 $\mu$ w/m$^2$</td>
</tr>
<tr>
<td>K</td>
<td>Thermal conductivity</td>
<td>3.0 w/m k</td>
</tr>
<tr>
<td>L</td>
<td>Thickness of lithosphere</td>
<td>120 km</td>
</tr>
<tr>
<td>ρ</td>
<td>Density of upper block</td>
<td>2.7 g/cm$^3$</td>
</tr>
<tr>
<td>R</td>
<td>Peclet number</td>
<td>$R = uL/2\alpha$</td>
</tr>
<tr>
<td>T</td>
<td>Time</td>
<td>A</td>
</tr>
<tr>
<td>T(z,t)</td>
<td>Instantaneous temperature structure</td>
<td>To be determined</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Temperature at the base of the lithosphere</td>
<td>1333ºC</td>
</tr>
<tr>
<td>τ</td>
<td>Thermal time constant of lithosphere</td>
<td>$\tau = ut/L^2$</td>
</tr>
<tr>
<td>U</td>
<td>Uplift rate relative to the bottom of lithosphere</td>
<td>mm/a</td>
</tr>
<tr>
<td>Z</td>
<td>Depth</td>
<td>km</td>
</tr>
<tr>
<td>$C_n$</td>
<td>Coefficient similar to Fourier coefficient</td>
<td>n=11, 23</td>
</tr>
</tbody>
</table>
FIGURE 1: THE CONCEPTUAL MODEL FOR CALCULATION OF THERMAL EFFECT OF UPLIFT.

Thickening of crust: $\Delta Z_1 = u_1 t_1$

Upper block $A_1 = 2.0 \mu W/m^3$

Lower block $A_2 = 0.5 \mu W/m^3$

(Initial temperature)

$u = 1, 3, 5, 7, 9, 11 \text{ mm/a}$

$t = 0.03, 0.1, 1, 3 \text{ Ma}$

FIGURE 2: VARIATION OF TEMPERATURE STRUCTURE IN CRUST BY HIGH-VELOCITY UPLIFTING IN QINGHAI-TIBET PLATEAU

1, 2, 3, 4, 5 in the figure roughly correspond to the end of Pliocene, Early-, Middle-, Late-Pleistocene and Holocene, respectively.
FIGURE 3: THERMAL EFFECT OF UPLIFTING OF QINGHAI-TIBET PLATEAU

1, 2, 3, 4 in the figure roughly correspond to the end of Pliocene, Early-, Middle-, Late Pleistocene plus Holocene, respectively.

The arrow in figure 3b indicates the direction that uplift velocity increasing along the curve.

The dot in figure 3b indicates the uplift velocity: 1, 3, 5, 7, 9 and 11 mm/a, respectively.