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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 chimnies" 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 Krafla, 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 374.1ºC and that of aqueous solution containing CO_2 and NaCl — approximately 400ºC.

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 anomaly resulting from heat points. In the Yangbajing-Yangyi basin, the youngest volcanic rocks on the earth surface are aged 9×10^6 years (Miocene). For a long time it has been considered that the highest temperature of hydrothermal water in Yangbajing is 150-172ºC. Even then, such temperature could not be explained as the confluence of regional terrestrial heat flow by way of deep circulation of ground water. Sub-volcano or "partial melting mass" must be inevitably inferred as the origin of the heat, in order to explain that there existed conditions for such a heat source, it is certain to associate it with some geological structure. The most popular idea is that the Indian Plate collides with and subducts under the Eurasian Plate, leading to local melting of the crust at the plate edge. The suture belt is located along the Yaluzangbu river, therefore in both sides of Yaluzangbu river and in South Tibet there existed intense geothermal activities.

To attribute the genetic type of high-enthalpy resources in Tibet with the Yangbajing-Yangyi geothermal fields as representative of the convergence belt of plates may fall into a difficult position scientifically. The results of a regional survey completed by parties of the Provincial Bureau Shaanxi in 1994 showed that the area of Yaluzangbu river is not a collision belt of two plates, but an intraplate rift-belt of the Indian Plate (China Geology and Mineral Resources News, 29/06/1994). Now that the suture belt as an indication of ocean crust extinction does not exist at all, correspondingly the originally so-called "plate edge" is not the edge of the plate. On the basis of detailed analysis of literatures and of comprehensive study, Zhao Zong-Pu (1994) put forward the concept that there does not exist "collision orogeny" on the continent, "the continental orogeny adheres to specific principles on formation and development which may independent of plate tectonic theory". It can be assumed that even if the geologists are able to identify convincingly the location of young plate-edge convergence belt, still the geothermics experts can not explain why the geothermal fields in Tibet have their heat sources from sub-volcano only, while they also belong to the global plate edge and to the high-enthalpy resources.

The known big "Heat Mining" areas in Qinghai—Tibet plateau are genetically of a new geological type. Their formation is related to large scale uplift accompanied Himalayan orogeny and result from high-speed uplifting and thickening of the earth crust, which led to the occurrence of high-enthalpy geothermal anomalies. We could call them geothermal fields of "uplift-thick crust" type.

3. THE CONCEPTUAL MODEL OF UPLIFT OF QINGHAI-TIBET PLATEAU

The conceptual model of uplift established for mathematical modeling is based on the physical nature and structure of material of the earth crust, as a result of orogeny-uplift, and on the process of uplifting with time. We adopted the information which has been summarized and generally acknowledged. The mechanism and dynamics of uplifting are not included in content of the model.

Both on satellite gravity and MAGSAT 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 Cretacious 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 Shamada 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 matetrials 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 and Middle Tertiary subtropical species indicated that at that time the altitude of the plateau above sea level was at most 2000-2500m.

The Qinghai-Tibet Comprehensive Survey Team of the Chinese Academy of Science (1980) determined that at the end of Pliocene the altitude of the plateau surface above sea level was 1000m. The uplift of Qinghai-Tibet plateau possibly underwent two stages:

—First stage, from Late Eocene-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 slowing 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 Kunlum 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 crust itself, the remaining part comes from the heat contribution of the upper mantle, i.e. the bottom of lithosphere. Besides, helium isotope determinations from geothermal steam in Yangbajing geothermal field indicate that these hydrothermal activities originate 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 0ºC to 800ºC; the lower block is cold — the temperature on the top is 0ºC and increases linearly downward to 1333ºC 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 are 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.

$$T(z,t)=T_R(z,t)+T_m[(1-e^{-2Rz/L})/(1-e^{-2R})]+T_m\sum C_n e^{-(n2}\pi^{2+R2)}\tau \; e^{-Rz/L}\sin(n\pi z/L) \qquad (1)$$

Where $C_n=(2/LT_m)\int_0^L\{T(Z,0)-T_R(Z,0)$

$$-T_m[(1-e^{-2Rz/L})/(1-e^{-2R})]\}e^{Rz/L}\sin(n\pi z/L)d_z \qquad (2)$$

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 (Figure1). Suppose the uplifting velocity of the crust equals thickening speed, i.e. to change the sign of parameter *u* (uplifting velocity) in the equation from positive to 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 Holocence 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 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 abscissa 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 uplift, the maximum temperature of the heat-front is basically in the range of granitic magma, 800-1100ºC. Broadly speaking, whenever yearly velocity increases by 1mm, the heat-front temperature increases by 40ºC. There existed an oscillatory correlation between uplift velocity and geotemperature, i.e. when velocity exceeds a certain value, there appeared a negative correlation, and when it exceeds again another certain value, the correlation becomes positive again, and the amplitude gradually decreases. At the moment, we can not confirm whether this phenomenon is real in the actual geology. It is worth noting that with the increase of uplift velocity and geotemperature, the depth at which the maximum temperature appeared increased correspondingly from 20 km to 40 km. This tendency was intensified under the influence of time effect of uplift (with the elongation of duration and the lowering of peak temperature of heat-front, the burial depth of the peak- value increased). As a result the depth of the peak value in the Late Pleistocene-Holocene (No.4 curve) reached 50 km, in other words, the magma batch, which already reached the melting temperature, will be more difficult to reach the earth surface.

The theory of "thermal effect of uplift" can provide a satisfactory explanation of the formation mechanism, as to how the high-enthalpy geothermal resources formed in Qinghai-Tibet and why the heat source has a certainly sub-volcanic environment.

(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 uplift 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.

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

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

Table 2: Values and Symbols Used

Symbol	Definition	Value
A	Initial depth to base of heat producing layer at t=0	38km(30 for upper block, 8 for lower block
α	Thermal diffusivity	$1\times10^{-6}m^2/s$
A(z+ut)	Heat production	Upper block 2.0μ w/m^3, lower block 0.5μ w/m^3
K	Thermal conductivity	3.0w/m k
L	Thickness of lithosphere	120km
ρ	Density of upper block	$2.7g/cm^3$
R	Peclet number	R=uL/2α
T	Time	A
T(z,t)	Instantaneous temperature structure	To be determined
T_m	Temperature at the base of the lithosphere	1333ºC
τ	Thermal time constant of lithosphere	$\tau=\alpha t/L^2$
U	Uplift rate relative to the bottom of lithosphere	mm/a
Z	Depth	km
C_n	Coefficient similar to Fourier coefficient	n=11,23

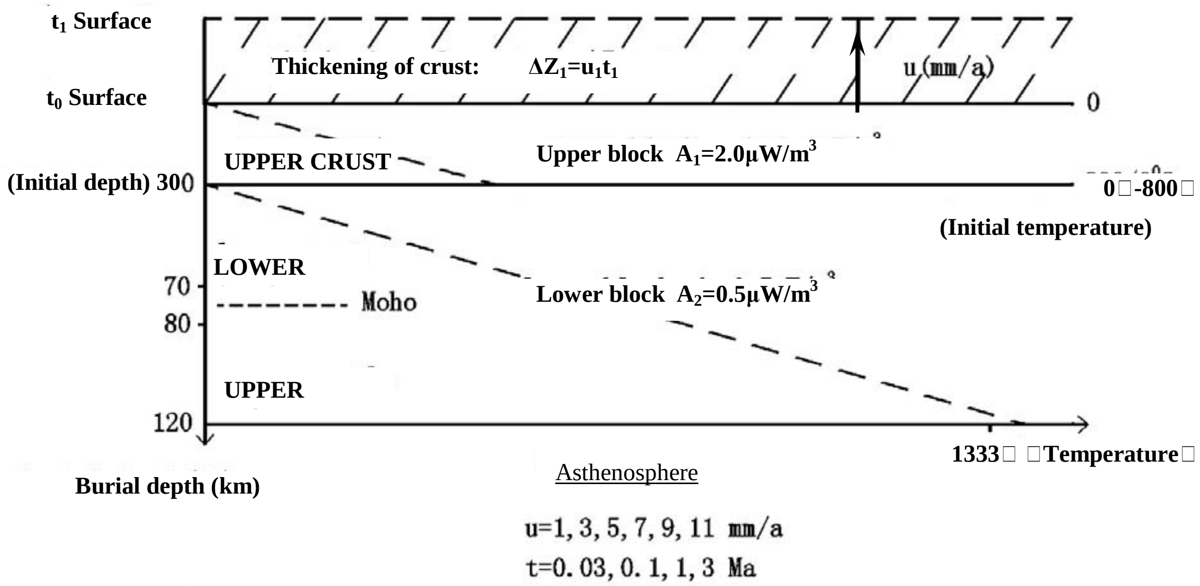

FIGURE 1: THE CONCEPTUAL MODEL FOR CALCULATION OF THERMAL EFFECT OF UPLIFT.

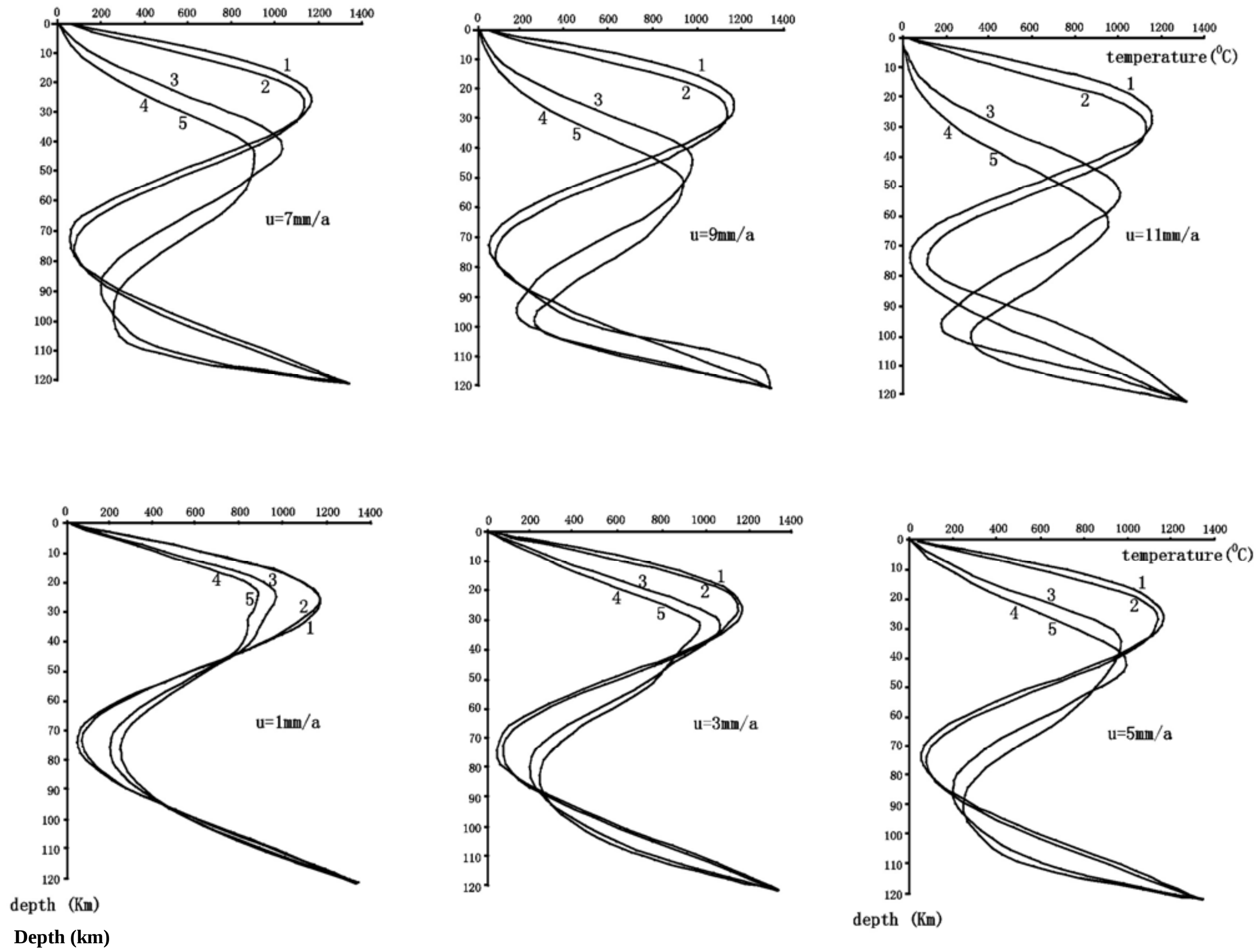

FIGURE 2: VARIATION OF TEMPERATURE STRUCTURE IN CRUST BY HIGH-VELOCITY UPLIFTING IN QINGHAI-TIBET PLATEAU

1,2,3,4,5 in the figure roughly correspond to the end of Pliocene, Early-, Middle-, Late-Pleistocene and Holocene, respectively.

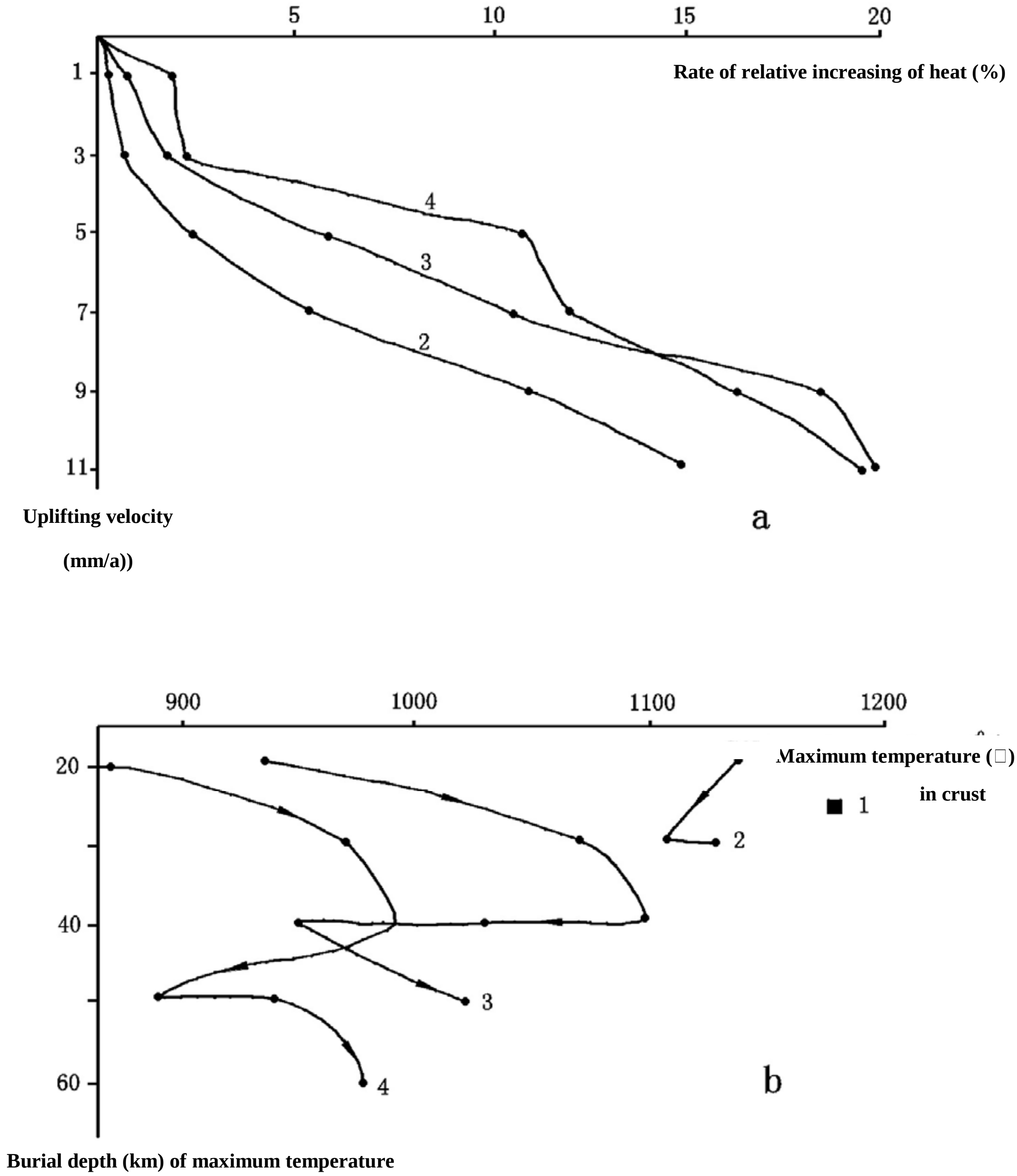

FIGURE 3: THERMAL EFFECT OF UPLIFTING OF QINGHAI-TIBET PLATEAU

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