An Introduction to the Academic Contribution of Zhi-Wei Yu

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Abstract

The academic contribution of Zhi-wei Yu mainly focus on two aspects which are complex geological surface interpolation model and Quaternary stratigraphy time scale calibration theory. First of all, Prof. Yu introduced the surface spline function in the field of Mathematical Geology and extended the original method of 2D interpolation to hypersurface spline method of 3D interpolation. Moreover, he developed a new geological surface interpolation called regionalized interpolation. Now, these methods are used as powerful geological surface interpolation tools. Besides, he proposed the automatic orbital tuning method for the Quaternary stratigraphy time scale and found the periodic characteristics of climatic evolution of the Quaternary period and major transformational events, these findings are of great significance to research in Quaternary climate change.

1. Complex Geological Surface Interpolation Model

1.1 Surface Spline Method to Interpolation

In coal exploration, one problem frequently encountered is the inference of the distribution of coal seams deeply buried as well as tectonic conditions with borehole data in a large area, which has been explored to a certain degree. The shape of coal seams is determined by the shapes of head plates and soleplates, so that the shapes of coal seams, if the shapes of coal bedding planes are known, can be obtained. From a mathematical perspective, this is a surface function approximation problem. The existing mathematical tools, such as a spline function, can form a smooth surface by interpolation with discrete data points; however, spline interpolation is generally required to meet strict conditions, difficult to meet in the actual geological conditions. To overcome this problem, Prof. Yu introduced for the first time the surface spline function to calculate the geological surface. This new interpolation method has a prominent advantage in that the plane coordinates of known points, whether regular or not, can obtain smooth surfaces of arbitrary order that are differentiable using natural boundary conditions(Yu, 1987 and 2001). The principle and process of the surface spline method is thus explained: Surface spline can be regarded as an infinite plane pure bending deformation.

According to the theory of elasticity, the differential equation between the deformation $w(x, y)$ and the on-board load $q(x, y)$ is expressed as:

$$D\nabla^4 W = q$$

Equation 1

with D representing the flexural rigidity of the plate. If the deformation of the plate is seen as a point load caused by given independent points, then the polar coordinates and the analytical expression for the surface spline are introduced as:

$$W(x, y) = a_0 + a_1 x + a_2 y + \sum_{i=1}^{n} F_i r_i^2 \ln(r_i^2 + \varepsilon)$$

Equation 2

with x and y as coordinates, $w(x, y)$ as some quantity of research interest, a_0, a_1, a_2, F_i (i=1,2,...,n) as the undetermined coefficients, $r_i^2 = (x - x_i)^2 + (y - y_i)^2$ and ε as the empirical parameter to adjust surface curvature. When the surface curvature largely changes, ε should be smaller than usual, and, on the contrary, ε should be larger. In general, ε ranges from 10^{-2} to 1 for flat surface and 10^{-6} to 10^{-5} for singularity surface. The N + 3 unknowns are determined from:

$$\begin{cases} W_j = a_0 + a_1 x_j + a_2 y_j + \sum_{i=1}^{n} F_i r_{ij}^2 \ln(r_{ij}^2 + \varepsilon) + c_j F_j \\ [j = 1,2,\cdots,n; r_{ij}^2 = (x_i - x_j)^2 + (y_i - y_j)^2] \\ \sum_{i=1}^{n} F_i = 0 \\ \sum_{i=1}^{n} x_i F_i = 0 \\ \sum_{i=1}^{n} y_i F_i = 0 \end{cases}$$

Equation 3

The coefficients Cj, which have units of length squared, are equal to $16\pi D/Kj$, where D is the plate rigidity and Kj is the spring constant associated with the jth point. From the Householder Transformation Algorithm, the column vector X, the solution of simultaneous, and linear equations, can be determined with stability. When the interpolation expression is obtained, the geological surface can be calculated by placing the plane coordinates and heights of some control points into the expression. Given the data from the website[1], the magnitude contours and surfaces drawn by the surfer software with the calculating results of surface spline method have been obtained, the illustrations of which are shown as follows:
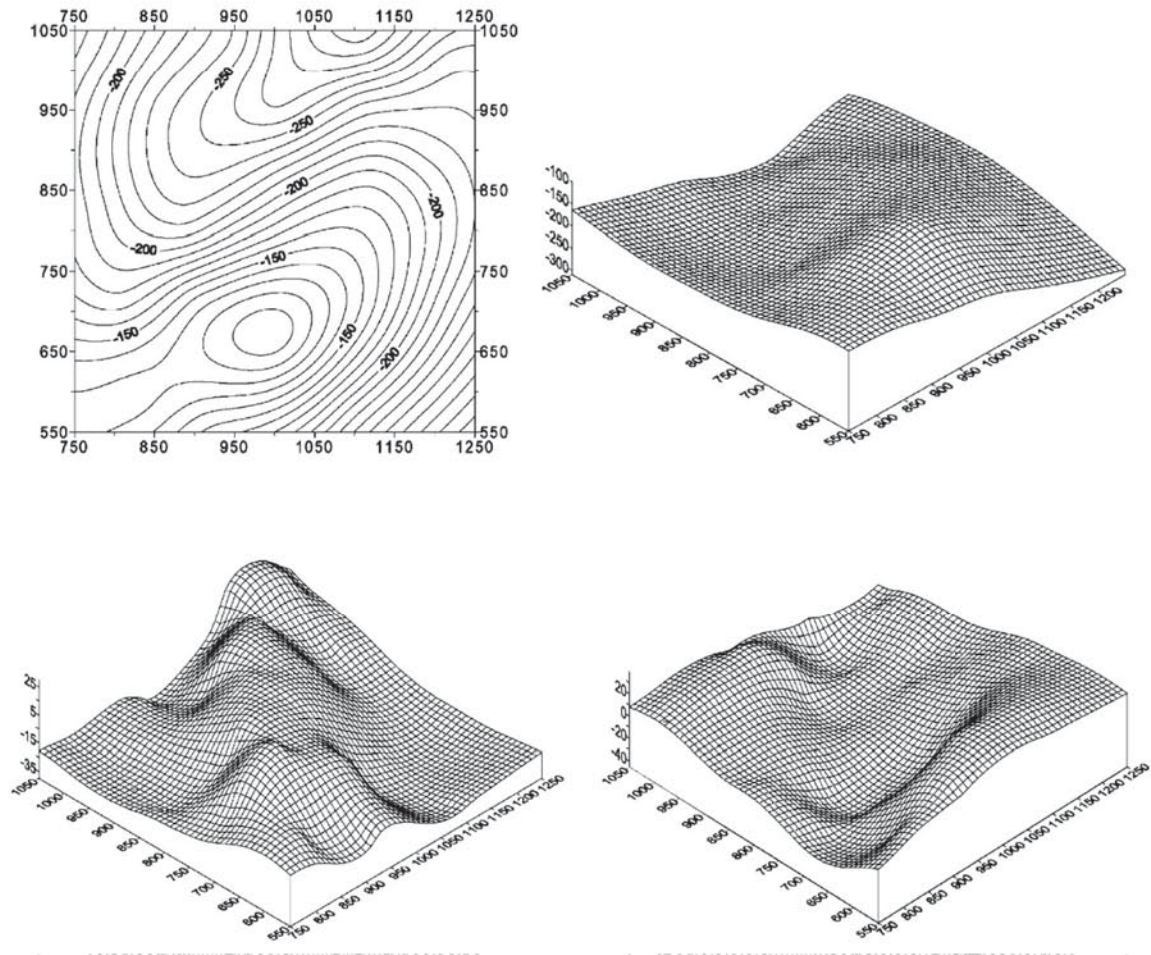

Illustration 1: shows the results generated by Surfer1 for Windows obtained by SSPL based on set of scattered data points. (A) Contour map, (B) 3-D surface plots of 51×51 grid, (C) SLX, slopes in *x* direction, (D) SLY, slopes in *y* direction, and input data values in file appendix-B.txt on IAMG server

[1]http://www.iamg.org/index.php/publisher/articleview/frmArticleID/104

The surface spline function is a continuous function, so it more realistically reflects a geological surface and the information regarding geological occurrence can be more easily obtained. The slopes of the geological surface in the x and y directions at the interpolated point are equal to the first partial derivatives of Equation (2), the surface spline function. Prof. Yu introduced the surface spline function to the field of Mathematical Geology and improved upon it so that it now can be utilized as a powerful geological surface interpolation tool. This is an entirely new innovation for geological automatic processing. With the help of software, a geological surface can now be automatically generated and drawn by a computer. Compared with traditional hand-drawn contours, those generated by the surface spline method are more objective, proper, and accurate. In addition, these computer-generated contours can also be conveniently modified and new data easily appended. The surface spline method is a new method for the approximation of geological surfaces, which interpolates geological surfaces from scattered data, and also provides a new tool for coal deposit modeling and mineral resources prediction.

1.2 Prof. Yu Extended the Original Surface Spline Method of 2D Interpolation to Hypersurface

The spline method of 3D interpolation is used to solve complex geological information retrieval problems. GIS technology has achieved great success in two-dimensional spatial information management. However, 3D information is generating more and more interest, in particular, the distribution of an object in 3D space (Rui et al., and Xu et al., 2001). Raw data and needed information of the three-dimensional space is usually discrete and difficult to obtain, thus requiring a special method to process and extract this useful information. Prof. Yu extended the original surface spline method of 2D interpolation to 3D space and presented the three-variable hypersurface splines method. The analytical expression for the surface spline is as follows:

$$W(x,y,z) = a_0 + a_1 x + a_2 y + a_3 z + \sum_{i=1}^{n} F_i r_i^2 \ln(r_i^2 + \varepsilon)$$

Equation 4

where W is the attribution of point in 3D space, x, y, z are the coordinates, and $r_{ij}^2 = (x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2$ The hypersurface spline method of 3D interpolation is a new method of 3D spatial interpolation, easy to implement and to obtain the attribution of any point in the space.
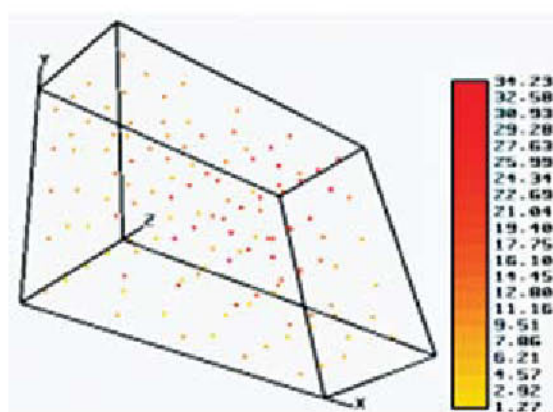

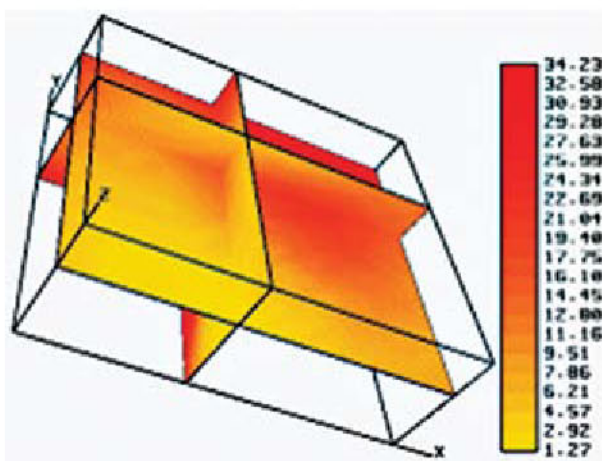Illustration 1: the original distribution of sample data

Illustration2: regular datasets processed by sectioning

Rui and Yu used this method to interpolate 3D temperature field data. Illustration 1 shows the distribution of the original sample data; Illustration 2 shows the distribution of regular datasets in space. They used this method for depth solution of geological surfaces in a particular exploration field based on the integration of elevation data obtained from drilling, and travel time data obtained from high-resolution seismic exploration. The relationship between travel time data and depth values are dependent on spatial coordinates x,y in the inversion area. The change of the depths (elevations) of geological surface is not a monotone function of the travel time of reflex wave, so a nonlinear mapping the measure data, D=D(x,y,t)into the image, I=I(x,y,z) is needed in depth solving based on travel time data and borehole data. The three-variable hypersurface splines developed based

on the two-variable surface splines is a suitable mapping function for this purpose. Employing this function, the travel time data can be globally inverted to the elevations of geological surfaces for a whole exploration field.

2.3 Regionalized Interpolation

While a geological surface is drawn, linear information sources are frequently used and usually dispersed into point-like information followed by interpolation. However, this treatment loses much information and distorts the shape of the 3D body. To take full advantage of abundant geological data accumulated in the coal production to draw a fine and highly reliable geological surface, Prof. Yu developed a new mathematical geology method called regionalized interpolation (Yu and Tan, 2002). Linear information sources include contours, fault lines, boundary lines, among other data, and the entire graph can be divided into a number of districts. The regionalized interpolation method adopts respective interpolation methods for districts surrounded by different lines. and, explained in detail.

2.3.1 Interpolation of the polygon surrounded by boundary lines having different elevations

In this case, the polygon is the area between two different elevation contours. It is a typical monoclinal stratum, so the elevation of the geological surface is found just between the two different elevation contours, thus making sense to approximate by linear interpolation.

23.2 Interpolation of the polygon surrounded by one boundary line

In this case, the elevation of the boundary line is the same. The polygon resembles a ring and it is a syncline or anticline fold; therefore, linear interpolation is obviously unsuitable. In order to obtain accurate elevation of any point in the polygon, to which type of polygon it belongs (syncline or anticline) is first decided; a secondary BEZIER curve is then used to approximate. A curve with a maximum between the elevation of two contours is determined, with a new curve and contours composing a fold.

2.3.3 The Method to deal with fault lines or subsided column

Handling fault lines has been a difficult problem in 3D simulation. Regionalized interpolation copes with this problem by adding fault lines into linear information sources and gives these lines higher weights than those of the contours.

The polygon is then divided into a number of districts by these lines. While interpolating, the splitting role of fault lines takes priority over other lines; thus, the geological surface on both sides of the fault lines has a discontinuous jump and forms a jump function. This method can also be applied when dealing with a subsided column.

2.3.4 The Way to cope with boundary lines

Boundary lines control the scope of region to interpolate and help to form a closed area. Applying the method that deals with fault lines to process the boundary lines, the elevation of points on boundary lines can be calculated and this information taken into interpolation. In this way, the entire region is divided into a number of districts by these lines; interpolation is then implemented in districts. In comparison with the traditional procedure, regionalized interpolation can not only effectively eliminate the information loss, but also make the surface map reconstruction more accurate. By means of regionalized interpolation, much existing geological information, including that regarding strata contours, fault lines, and borderlines, can be converted into digital information and then incorporated into a GIS database. Reconstruction of fault lines has always been a difficult task in 3D simulation. Research results and case studies clearly demonstrate that a new method has been found to properly deal with this problem. The key of the settlement of the fault problem lies in the combination of the strata and the fault information. Concrete steps include: finding the intersection of strata contour with fault line; and then obtaining strata elevation values of each such intersection point. Like a strata contour line or a stratigraphic borderline, fault lines act as a borderline surrounding a sub-area. Geologically, however, the adjacent sub-areas on both sides of this fault line are not continual, so the details of the adjacent sub-areas can be reflected on the reconstructed surface map. Other borderlines can also be treated as a fault line. Therefore, the entire study area can be divided into sub-areas by these borderlines, fault lines, and strata contours. Inside these sub-areas, a suitable method can be applied to obtain proper interpolation results. On the basis of interpolation in each and every sub-area, a surface map can be reconstructed for the entire study area. Increments in data input resulting from data collection and preprocessing are valuable in surface reconstruction with higher accuracy.

3. Quaternary Stratigraphy Time Scale Calibration Theory

3.1 Automatic Orbital Tuning Method for the Quaternary Stratigraphy Time Scale

Paleoclimate records have four basic characteristics which need to be determined: time scale; periodicity; spectrum characteristics and the phase relationship of the paleoclimate records and climate-driven factors; as well as the phase relationship between the climatic proxy indicators (Yu and Ding, 2001). Only by knowing these basic characteristics can the evolution model of ancient climate change is further developed. Among these characteristics, first of all, an accurate time scale of proxies for Quaternary climate change has to be created. To achieve this objective, the so-called orbital tuning method has been developed, currently widely used in establishing time scales for various climate records. Several internationally well-known time scales, such as the SPECMAP, among other scales, are the results of the orbital tuning method. Although the details of the procedure used by different authors can differ, most of the orbital time scales are essentially established in the following three steps (Ding et al., 1994). First, the theoretically-calculated changes in the Earth's orbital elements are applied as the tuning target. An initial time scale is then constructed by interpolating the paleoclimate data between the time control points derived from independent geochronological studies. Finally, digital filters are repeatedly applied to extract the orbital frequency components from the paleoclimate records plotted against the initial time scale. The filtered curves are then aligned against the corresponding phase-locked orbital signals by adding new time control points. In so doing, a good fit between climatic records and variations in the Earth's orbits can be generally obtained both for phasing and periodicity. Before the proposal of automatic orbital tuning method, most of the tuning methods established required visual judgments in adding new time control points into the climate records for which an orbital time scale was thus developed. As a result, these methods had shortcomings, such as: operability and objectivity were poor; the work was also time-consuming in obtaining the final version of the time scale due to the fact that repeated changes of the time control points had to be performed. The time scale is just a space-time conversion, determined by obtaining the time coordinates from the spatial coordinates of sampling points; fortunately, this can be efficiently and accurately be determined by utilizing the Dynamic Optimization Method, which lacks the shortcomings of the previous methods cited (Yu et al., 1996). A primary paleoclimate record derived from analysis of geological sediments consists of a series of data points along a depth profile (Ding et al., 1994 and Yu and Ding, 2003), and can be defined as $c(d(i))(i=0,1.. ... N, N+1)$, where $d(i)(i=0,1.. ... N, N+1)$ is a depth series, and $c(d(0))$ represents the data point at the top of the profile and $c(d(N+1))$ at the bottom. To establish a time scale $t(i)(i=0,1 ..... N, N+1)$ for this climate record, an age must be assigned to $d(i)(i=0,1.. ... N, N+1)$ under the control of independent chronological data, achieved by tuning the climate record $c(d(i))$ to selected target curves. The resultant time series of the climate record can then be referred to as $c(t(i))(i=0,1. .... N, N+1)$. Among the three orbital parameters, obliquity and precession are generally used as the tuning target, and can be respectively defined as $O(j)(j=1,2 ..... M)$ and $P(j)(j=1,2 ..... M)$. In order to examine the fitness of the tuned climate time series $c(t(i))$ with target curves, a criterion must be developed. The filtered $O(j)$ from the $c(t(i))$ is defined as $X_1(j)(j=1,2 ..... M)$, and the filtered $P(j)$ as $X_2(j)(j=1,2. .... M)$. The respective correlation coefficients between the filtered $O(j)$ and the obliquity curve and between the filtered $P(j)$ and the precession curve are used as the criterion. Two correlation coefficients can thus be calculated as:

$$R_1 = \sqrt{\frac{\sum_{j=1}^{m}(X_1(j)-\overline{X_1})(O(j)-\overline{O})}{(m-1)\sum_{j=1}^{m}(X_1(j)-\overline{X_1})^2 \sum_{j=1}^{m}(O(j)-\overline{O})^2}}$$

$$R_2 = \sqrt{\frac{\sum_{j=1}^{m}(X_2(j)-\overline{X_2})(P(j)-\overline{P})}{(m-1)\sum_{j=1}^{m}(X_2(j)-\overline{X_2})^2 \sum_{j=1}^{m}(P(j)-\overline{P})^2}}$$

Equation 5

where X_1, X_2, $\overline{O}$ and $\overline{P}$ represent the average of $X_1(j)$, $X_2(j)$, $O(j)$ and $P(j)$, respectively. The best fit between the tuned climate time series and the target records should have the highest values of both R_1 and R_2. In the Dynamic Optimization Method, each of the data points, except $t(0)$ and $t(N+1)$ in $t(i)(i=0,1,2 ..... N, N+1)$, is regarded as a variable. The best age assignment for each needs to be calculated. The detailed procedure of the automatic orbital tuning is described as follows:

(1) To select target curves $O(j)$ and $P(j)$

(2) To establish an initial time scale for the climate-proxy record. This is obtained by

interpolating the data points in t(i) between independent geochronological control points. In general, additional time control points are needed to result in a relatively good match between initial $X_1(j)$ and $O(j)$ and between initial $X_2(j)$ and $P(j)$ and to save computing time. The additional time control points can be read from the visual correlation between climate records and the target curves. In this way, an initial t(i) is constructed.

(3) To calculate the initial values of R_1 and R_2

(4) To generate a new t(i) using the Dynamic Optimization Method. In the initial t(i)(i=0,1,2 ..... N, N+1), the age for each of the climate-proxy data, for example t(1), needs to be repeatedly altered to produce a best match between c(t(i)) and with the O(j) an P(j). This is accomplished in this method by fixing the age of the data points t(2) to t(N) in the t(i), thus allowing t(1) descend or ascend at a select iterating step over the interval of t(0) and t(2). For each iterating step, R_1 and R_2 are calculated so that a "best" age of t(1) is obtained and the age of t(1) in t(i) can be contemporarily fixed. In the same way, the "best" ages of t(2) to t(N) are calculated.

(5) To obtain the final version of t(i) by repeating (4). When the highest R_1 and R_2 values are obtained, the orbital time scale can be finally established.

An accurate time scale is the pre-condition for paleoclimate records that are used to study the time-dependent changes in climate periodicity and to determine the phasing relationship with other records. In regional climate change studies, once a time scale in a standard section is established, it can be directly used to date climatic events identified in other sections. This is particularly true in studies of the loess deposits in China and deep-seas sediment because of their completeness in recording the climate history in the Quaternary. Therefore, techniques that allow an objective, fast establishment of time scales are widely needed. The method proposed in this paper differs from the classic orbital tuning method. Compared to the latter, this automatic tuning method appears to better satisfy this requirement. In addition, this new method can result in a climate time series with higher time resolution relative to the classic one. In the classic tuning procedure, the climate-proxy data between two time control points are linearly interpolated, so each piece of data has the same time interval between the two control points.

In the AOTM-tuned time series, the age for each of the climate data can be calculated, thus resulting in a higher resolution.

3.2 The Application of Automatic Orbital Tuning Method in the Research of Paleoclimate Changes during Quaternary Period

It is apparent that there are three periods in various Quaternary paleoclimate records: the period of the Earth's orbital eccentricity cycles, ~100 ka; the period of the Earth's obliquity cycles, 41 ka; and the periods of the precession cycles, 23 ka and 19 ka (Yu et al., 1996 and Yu, 1994). Existing studies have shown that the obliquity and the precession were major linear forces of paleoclimate changes during Quaternary period (0.0-2.6 Ma). Both theoretical calculations and paleoclimate records show that a group of periods ranging from 75 ka to 126 ka constitute ~100 ka cyclicity, unstable during Quaternary period. It is generally accepted that this 100 ka cycle represents a major component of the record of changes in total Northern Hemisphere ice volume. It is difficult to explain this predominant cycle in terms of orbital eccentricity because the 100 ka radiation cycle (arising from eccentricity variations) is far too low in amplitude to produce the corresponding climate cycle by direct forcing. Therefore, the cause of 100 ka cyclicity presented in late Quaternary poses one of the perplexing problems in paleoclimatology. To solve this problem, Prof. Yu probed the nonlinear responsive relationship between 100 ka cyclicity and other cyclicities. Lingtai and Jingchuan loess sections in China in addition to the Chashmanigar sections in Tadzhikistan were used as study objects and the median grain size (MD) employed as the climate proxy. In his study, Prof. Yu applied the automatic orbital tuning method to establish timescales of the three sections, whose analysis shows that the time series of the three sections are coincident concurrent in main depositional cycles, resulting in comparable recorded climate change signals (Yu et al., 1993). For further detection of paleoclimate periodicity of the three sections, power spectra were conducted. The results show that the spectrum peak of 100 ka is weak from 0.8 Ma to 1.2 Ma and strong during the other intervals (1.2 Ma to 2.6 Ma and 0.0 Ma to 0.8 Ma (Yu et al., 1993). In the following, Prof. Yu employed the bispectral analysis to detect phase coupling between 100 ka and the other periodicities related to obliquity, precession, and semiprecession. A normalized form of the bispectrum, called the bicoherence or auto-bicoherence, was then used as an alternative indicative of quadratic phase coupling, concluding that the origin of 100 ka periodicities in variability of the climate may be

related to quadratic phase coupling between precession and semiprecession (Yu et al., 1992, Ding, 2001 and Ding and Yu, 1995). This work provides a light in the resolution of the problem of 100ka cyclicity.

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Short Biography Zhi-wei Yu

Zhi-wei Yu was born in Wuxi, Jiangsu Province, in September, 1956. At a very young age, he became a Professor in the College of Geoscience and Surveying Engineering at China University of Mining and Technology (Beijing). Prof. Yu has been engaged in research fields, such as Cartography and Geographic Information Systems, Earth Exploration, Information Technology, and Quaternary Geology and Paleoclimate. In addition, Prof. Yu's findings won 3rd prize in the Ministry of Coal Science and Technology Progress and 3rd prize in the State Education Commission of Science and Technology Progress. Moreover, in 1994 one of his findings was listed as one of the 16 major achievements in Earth Sciences by the National Natural Science Foundation Committee. Prof. Yu has the indubitable distinction to have introduced the surface spline function in the field of Mathematical Geology and improved it to expand the scope of its use. As a result, the surface spline function can now be used as a powerful geological surface interpolation tool. In recent years, he has extended the original surface spline method of 2D interpolation to hypersurface spline method of 3D interpolation to solve complex geological information retrieval problems (e.g., coal geology concealed structure). As per the requirements of mine geological information technology, Prof. Yu developed a new method in Mathematical Geology called regionalized interpolation, another new geological surface interpolation, which followed the surface spline function. In the late 1990s, this distinguished Professor proposed the automatic orbital tuning method for the Quaternary stratigraphy time scale, a great innovation in the methodology in Quaternary Geology and Paleoclimatology. By analyzing the paleoclimate time series recorded by loess, Prof. Yu exposed the periodic characteristics of climatic evolution of the Quaternary period and major transformational events, findings that are of great significance to research in Quaternary climate change.