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Visualization and dissemination of global crustal models on virtual globes

Liang-feng Zhu*, Xin Pan, Jian-zhong Sun

Key Laboratory of GIS for Ministry of Education, East China Normal University, Shanghai 200241, China

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ABSTRACT

Global crustal models, such as CRUST 5.1 and its descendants, are very useful in a broad range of geoscience applications. The current method for representing the existing global crustal models relies heavily on dedicated computer programs to read and work with those models. Therefore, it is not suited to visualize and disseminate global crustal information to non-geological users. This shortcoming is becoming obvious as more and more people from both academic and non-academic institutions are interested in understanding the structure and composition of the crust. There is a pressing need to provide a modern, universal and user-friendly method to represent and visualize the existing global crustal models. In this paper, we present a systematic framework to easily visualize and disseminate the global crustal structure on virtual globes. Based on crustal information exported from the existing global crustal models, we first create a variety of KML-formatted crustal models with different levels of detail (LODs). And then the KML-formatted models can be loaded into a virtual globe for 3D visualization and model dissemination. A Keyhole Markup Language (KML) generator (*Crust2KML*) is developed to automatically convert crustal information obtained from the CRUST 1.0 model into KML-formatted global crustal models, and a web application (*VisualCrust*) is designed to disseminate and visualize those models over the Internet. The presented framework and associated implementations can be conveniently exported to other applications to support visualizing and analyzing the Earth's internal structure on both regional and global scales in a 3D virtual-globe environment.

1. Introduction

As the Earth's outermost solid shell, the crust comprises a critical zone that participates in and controls processes of Earth's deep interior as well as in the atmosphere (Laske, 2014). On the global scale, the crust possesses a complex structure with diverse compositions. Variations in the thickness and composition of individual sublayers within the crust significantly influence the spatial variation of Earth's magnetic and gravitational fields. Over the years, a number of global crustal models with various levels of detail, such as 3SMAC (Nataf and Ricard, 1996), CRUST 5.1 (Mooney et al., 1998a; Mooney et al., 1998b), CRUST 2.0 (Bassin et al., 2000; Laske et al., 2000), CRUST 1.0 (Laske et al., 2013) and LITHO1.0 (Pasyanos et al., 2014), have been presented to depict structural features and property parameters of the Earth's crust. These models are generally in the forms of computer codes and corresponding model files. In order to read and work with these models, users must delve into data formats specific to given missions, and develop dedicated computer programs or systems for visualizing and analyzing the structure of the crust. For example, CRUST 5.1 and its descendants provide Fortran computer codes and *xyz*-formatted model files for scientific users (Mooney et al., 1998a; Laske et al., 2000; Laske et al., 2013). This representation has serious limitations because it is only feasible for academic investigators, who are typically located at universities or research institutions, to conduct professional geological and geophysical research (Laske, 2014). With increased attention paid to the Earth's deep interior, more and more people, including atmospheric scientists, educators, policy-makers and even the general public, are getting interested in the 3D structure and composition of the Earth's crust. The current method for representing the structure of the crust becomes insufficient as it is difficult to respond to the demands drawn from these users. There is a pressing need to provide a more modern, universal and user-friendly method to represent and visualize the existing global crustal models.

The emergence of virtual globes provides an innovative opportunity for geoscientists to represent, disseminate and visualize geospatial information, including global crustal information. In the last 10 years, a number of sophisticated and powerful online

* Corresponding author.
E-mail addresses: lfzhu@geo.ecnu.edu.cn (L.-f. Zhu), xpan@admin.ecnu.edu.cn (X. Pan), sunjzh2007@gmail.com (J.-z. Sun).

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virtual globes, typified by Google Earth and NASA's World Wind, have been developed and applied to transform our capability to visualize and hypothesize in three dimensions (Butler, 2006). As digital models of the entire planet, virtual globes not only offer users the capability to image, analyze, synthesize and interpret geospatial objects on different spatial scales, but also can be regarded as reliable platforms for exploring, discovering, analyzing, exchanging and sharing geospatial information at regional or global scales (Butler, 2006; Tiede and Lang, 2010; Bailey and Chen, 2011; Goodchild et al., 2012; Yu and Gong, 2012; Liang et al., 2014; Mahdavi-Amiri et al., 2015; Tian et al., 2016). In recent years, a number of research teams have invested considerable effort in modeling and visualizing geospatial objects on virtual globes, especially Google Earth. With joint efforts contributed by Earth scientists and virtual globe developers, a number of techniques have been proposed and applied to address the needs of communicating and visualizing subsurface information in 3D virtual-globe platforms (Yamagishi et al., 2010, 2011; De Paor and Pinan-Llamas, 2006; De Paor and Whitmeyer, 2011; De Paor et al., 2011; Postpischl et al., 2011; Mochales and Blenkinsop, 2014; Zhu et al., 2014a, 2014c; Lewis and Hampton, 2015). However, the existing research only concerned the representation and visualization of subsurface models within local or regional areas. There is currently no readily available method for representing the global crustal structure on virtual globes. Therefore, it is a clear need to develop a universal method for the representation, dissemination and visualization of the global crustal structure on virtual globes.

In this paper, we explore the representation techniques and associated implementation methods for visualizing the global crustal structure on virtual globes. Our ultimate goal is to establish a systematic framework, within which the location and variation of the Earth's crust may be represented, visualized and disseminated on virtual globes over the Internet. In order to fulfill this goal, we adopt the recently released Global Crustal Model CRUST 1.0 as the research object, and choose the Google Earth virtual globe as a platform for visualizing and distributing the global crustal information. This paper first summarizes the essentials of the CRUST 1.0 model, and then puts forward a general framework for the representation, visualization and dissemination of the existing global crustal models. Subsequently, key steps for performing the proposed framework are illustrated in great detail. The implementation program and its web application (⟨http://www.visualearth.org/globalcrust10/crust10web/visualcrust10.html⟩) are finally described.

2. Global crustal model CRUST 1.0

In July 2013, CRUST 1.0, a global crustal model at a $1° \times 1°$ resolution, was first formally released by Laske et al. (2013). As an updated version of CRUST 5.1 (a global crustal model at a $5° \times 5°$ resolution) and CRUST 2.0 (at a $2° \times 2°$ resolution), CRUST 1.0 incorporated a wealth of newly available data on global surface topography, seafloor bathymetry, seismic refraction, as well as the thickness data of ice, sediment and the crust. Therefore, it is the most detailed global crustal model of the moment, and might be widely embraced by Earth scientists in the foreseeable future.

As shown in Fig. 1, CRUST 1.0 consists of 64800 $1° \times 1°$ cells arranged in a fixed latitude-longitude grid (Laske et al., 2013). In each cell, the crust is described vertically by eight geophysically identified sublayers: (1) water, (2) ice, (3) upper sediments, (4) middle sediments, (5) lower sediments, (6) upper crust, (7) middle crust, and (8) lower crust. In order to make the model as complete as possible, water and ice are included in the CRUST 1.0 model as the first two sublayers (Mooney et al., 1998b; Laske et al., 2013). For each sublayer, the boundary depth and physical properties, including density ρ, compressional wave velocity V_p and shear wave velocity V_s, are specified to depict the variation of the crustal thickness and associated properties.

3. Overall framework

All current major virtual globes, including Google Earth and other comparable online Earth browsers, provide users with powerful and flexible rendering tools for visualizing geospatial objects in a 3D virtual environment, as they all support the OpenGIS KML Encoding Standard (OGC KML) (Wilson, 2008; Wernecke, 2009). OGC KML is a popular, pervasive and international standard for expressing and displaying geospatial objects within Internet-based 2D maps and 3D virtual globes. For the convenience of representing geospatial objects, KML provides a series of geometry elements (such as <Point>, <Polygon> and <Model>) and feature elements (such as <Placemark> and <GroundOverlay>) to describe "what" is embedded in the "where" and "when" of digital globes. Users of virtual globes only need to describe geospatial objects in accordance with the KML Encoding Standard, and then the existing virtual globes can identify, visualize and disseminate these objects automatically (Ballagh et al., 2011; Zhu et al., 2014b). According to this scheme, we present a

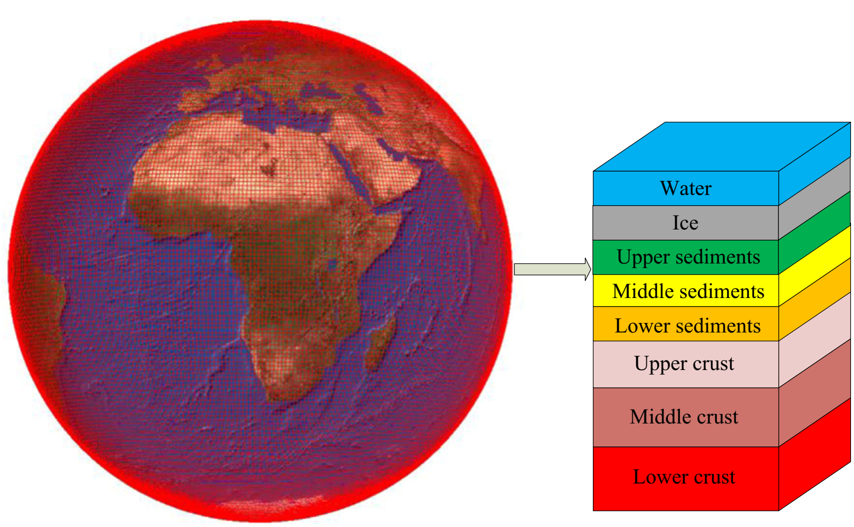

Fig. 1. Crustal structure representation implemented in CRUST 1.0. The crust is parametrized laterally by 64800 $1° \times 1°$ latitude-longitude grids and vertically as eight geophysically identified sublayers.

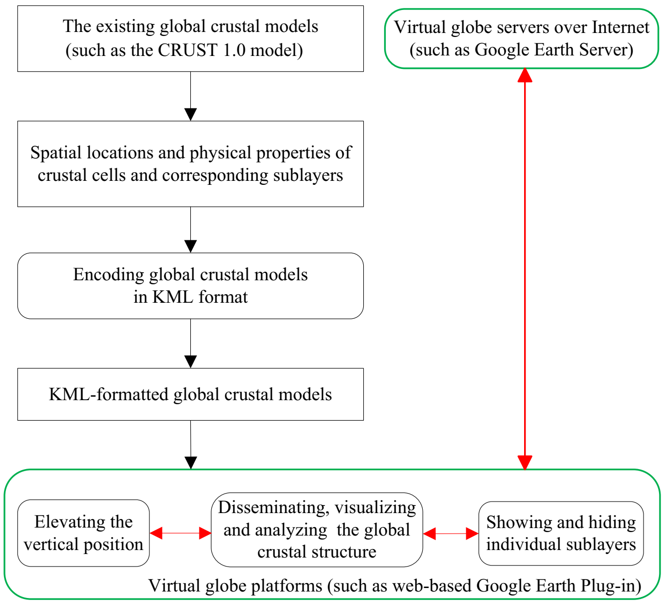

Fig. 2. The overall framework for representing, visualizing and disseminating global crustal models on virtual globes. The models and data sets are represented by the sharp-cornered rectangles; the program components that process those models are represented by the round-cornered rectangles. The black arrow lines denote the data flows in the framework; and the red double-headed arrows depict the graphical user interface controls and interaction between the program components and its user. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

general framework to support the representation, visualization and dissemination of the existing global crustal models on virtual globes. The overall process for this framework is illustrated in Fig. 2.

4. Key steps

The implementation of the proposed framework can be divided into five key steps, and the step-by-step execution is explained below.

4.1. Exporting global crustal information from CRUST 1.0

The first step is to export the global crustal information, including spatial locations and physical properties of individual crustal cells and corresponding sublayers, from the CRUST 1.0 model. The crustal information will be used for subsequent digital model creation and visualization.

For individual cells at the scale of $1° \times 1°$, we first extract the center coordinates (latitude and longitude) of the cells, as well as the average thickness and associated physical properties (density, V_p and V_s) of each sublayer, and then store them in a datasheet (recorded as "Cell Information Datasheet"). We represent sublayers within crustal cells as hexahedron elements.

Each hexahedron has 8 nodes. Using CRUST 1.0, we can calculate the 3D coordinates (latitude, longitude and altitude) and associated properties (density, V_p and V_s) of the nodes, and store them in another datasheet (recorded as "Node Information Datasheet").

4.2. Creating polygon placemarks representing top surfaces of crustal cells

The top surface of a crustal cell is the top surface of its first sublayer (the topmost sublayer). It can be draped over the Earth's terrain surface to reflect the spatial distribution of crustal cells. In the second step, the center coordinates and physical properties of crustal cells are firstly extracted from "Cell Information Datasheet". Then, by employing KML <Placemark> elements, a series of polygon placemarks are generated to represent top surfaces of crustal cells on the Earth's surface.

4.3. Building 3D solid models representing sublayers within crustal cells

Since sublayers possess the structural characteristics of stratification, sequentiality and continuity (Turner, 2006; Zhu et al., 2012; Zhu et al., 2013), the hexahedron model can be employed to represent each sublayer within a given crustal cell. The surface of a hexahedron can be represented by the KML <Polygon> element, and multiple surfaces belong to the same sublayer can be collected by the KML <MultiGeometry> element to construct a 3D solid model. In the third step, we first build individual hexahedron models to represent sublayers, and then combine them into a KML <Document> element.

The crust is situated below the Earth's surface. The Google Earth virtual globe lacks necessary function in visualizing subsurface features as they are hidden by the terrain (De Paor, 2008; Postpischl et al., 2011; Zhu et al., 2014c). That is, subsurface objects cannot be visualized in the correct locations beneath the surface of the Google Earth virtual globe. In order to visualize the crust, we elevate the vertical position of the crust by setting an uplifted height value. The individual sublayers within a crustal cell are positioned at the correct latitude and longitude, but their altitudes are elevated to display them above the globe's surface.

4.4. Representing the global crust with multiple scales

There are 64800 crustal cells in the CRUST 1.0 model, and each cell consists of a series of sublayers represented by hexahedrons, each of which is constructed by 8 nodes and 6 surfaces. It is obvious that the global crustal model is vast in data volume and complicated in geometrical structure. Due to its big size and complex geometry, real-time rendering of the global crustal model is a problem. Using the current computer hardware, it is either hard or impossible to simultaneously load and visualize all crustal cells and their sublayers. In order to improve the efficiency of visualizing the global crustal model, the KML Level of Detail (LOD) element and "Region" concept needs to be implemented (Wernecke, 2009). The main work of the fourth step involves creating the global crustal model that can be shown in three scales, and defining the control parameters to load and display the different LODs of the global crustal model.

In Earth science, the scale of an object is related to LOD describing a certain object within a given space (Zhu et al., 2007; Zhu et al., 2014a). In virtual globes, LOD refers to generating and delineating a series of target models from a source model, and the details of the target models are changing gradually. To visualize the global crustal model on virtual globes, the crust is represented in three discrete LODs: the less detailed level (LOD0), the moderate detailed level (LOD1) and the most detailed level (LOD2). LOD0 is defined by a 2D representation of the spatial distribution for all crustal cells. It contains neither property information nor interior sublayers. Therefore, it can be implemented by a raster image that can be draped onto the terrain. Since LOD0 possesses the minimal data volume with the simplest structure, it is suitable for occasions when the overview of crustal cells at a global scale needs to be displayed with lower resolutions. In LOD1, each cell is represented by the top surface of the first sublayer within the cell, and is defined by a 2.5D vector polygon that can be overlapped on the Earth's surface. The property information of the cell and its first sublayer is presented explicitly, but any details of the interior

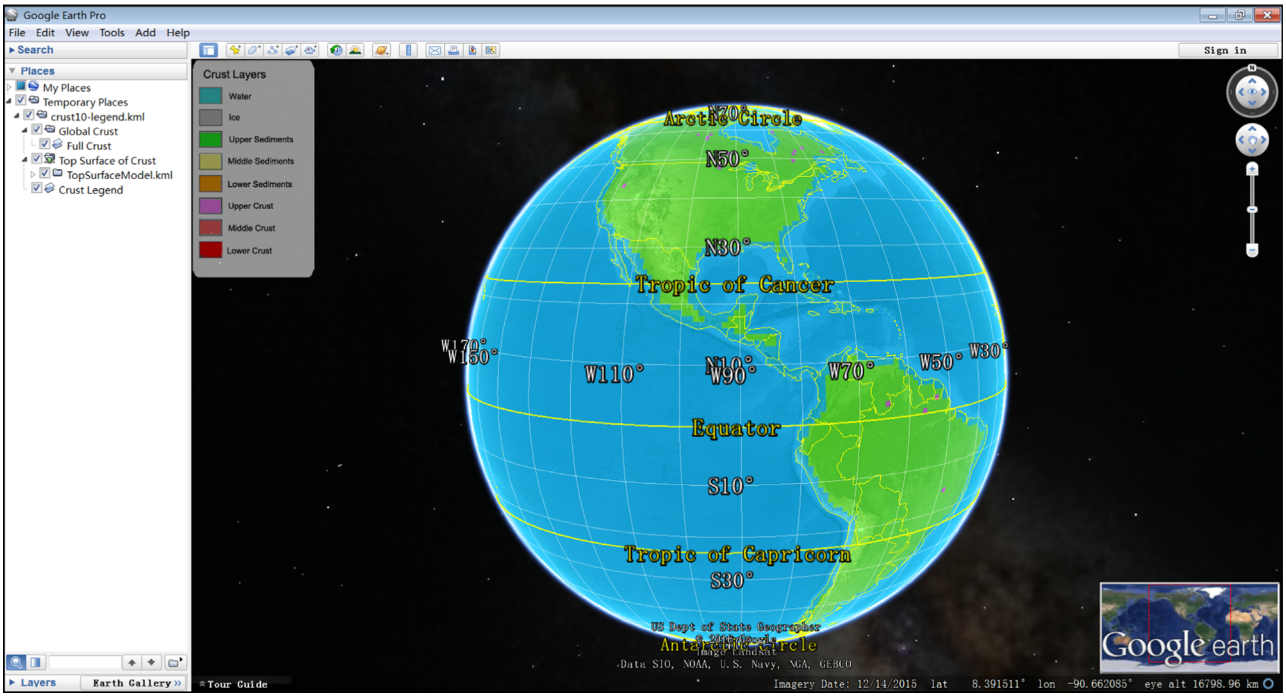

Fig. 3. Displaying the global crust with the less detailed level (LOD0) in Google Earth.

sublayers cannot be distinguished. The crust in LOD1 is designed for the visualization of crustal cells at local or regional scales. In LOD2, interior sublayers of the crust are added. Sublayers within individual cells are given as very detailed 3D solids, and the property information of each sublayer is also represented in a very detailed way. Because of the sheer volume and complicated structure of the data, LOD2 only applies to reveal detailed information about crustal cells within a very limited range.

The crust in LOD0 can be constructed from polygon placemarks of all crustal cells, which are generated in the second step. We put all polygon placemarks together and export a raster image (such as a PNG-formatted image file) to represent the crust in LOD0. Moreover, polygon placemarks for top surfaces of crustal cells can be directly used to represent the crust in LOD1, and 3D solid models for sublayers (generated in the third step) can be used to represent the crust in LOD2.

After creating the global crustal model in three LODs, the LOD-based rendering strategy is employed to automatically control the sequence of loading and displaying different LODs (Zhu et al., 2014c).

4.5. *Visualizing and disseminating the global crustal structure on virtual-globe platforms*

Finally, the KML-formatted global crustal model is loaded into a virtual globe (like the stand-alone Google Earth desktop application, or the web-based Google Earth plug-in) for 3D visualization and model dissemination. In virtual-globe platforms, polygon placemarks representing crustal cells are draped over Earth's terrain surface to represent the spatial distribution of crustal cells, and 3D solid models representing sublayers are used for visualizing and analyzing the internal structure within each crustal cell. The property data associated with crustal cells and their sublayers are added to KML placemarks by using the KML <ExtendedData> and <Data> elements, and then can be displayed in the descriptive balloon. Using the mouse, keyboard and other graphical interactive devices, we can arbitrarily choose crustal cells (or their sublayers) to observe their geometry structure and query their property information. Therefore, it opens up more possibilities to showcase the spatial distribution and property characteristic of the global crust in a visual, intuitive, appealing and interactive way.

Using Google Earth application programming interface (API), the Google Earth virtual globe instance can be embedded into a web application to distribute and view the global crustal model on the Internet (De Paor and Whitmeyer, 2011). Furthermore, by utilizing the Google Earth API to control the visualization of KML geometry elements, it is also possible to implement such advanced functions as manually elevating the vertical position of subsurface crustal sublayers (De Paor and Whitmeyer, 2011; Dordevic, 2013; Zhu et al., 2014b), and interactively controlling the visibility of each sublayer within crustal cells through a series of interactive map keys (Dordevic, 2012).

5. Implementation and application

To implement the proposed framework, a program, termed *Crust2KML* (CRUST 1.0 to KML), is developed with Python. *Crust2KML* is a KML generator that automatically converts crustal information derived from the CRUST 1.0 model into KML format. It enables us to easily visualize the global crustal structure, including the spatial distribution of individual crustal cells and their sublayers, on virtual globes without any additional processing of the model files.

The KML-formatted global crustal models created by *Crust2KML* can be found at 〈http://www.visualearth.org/globalcrust10/crust10web/help/crustalmodel.rar〉. Those models can be loaded into the Google Earth desktop application (or other comparable virtual globes) and explored with different viewpoints. As shown in Fig. 3, when we first pan to the digital globe from very far away, the global crust in LOD0, represented by a raster image draped over the solid Earth terrain model, first appears in the Google Earth container. As the view moves closer, the crust in LOD1 is loaded automatically, and polygon placemarks representing top surfaces of crustal cells come into view. Choosing a polygon

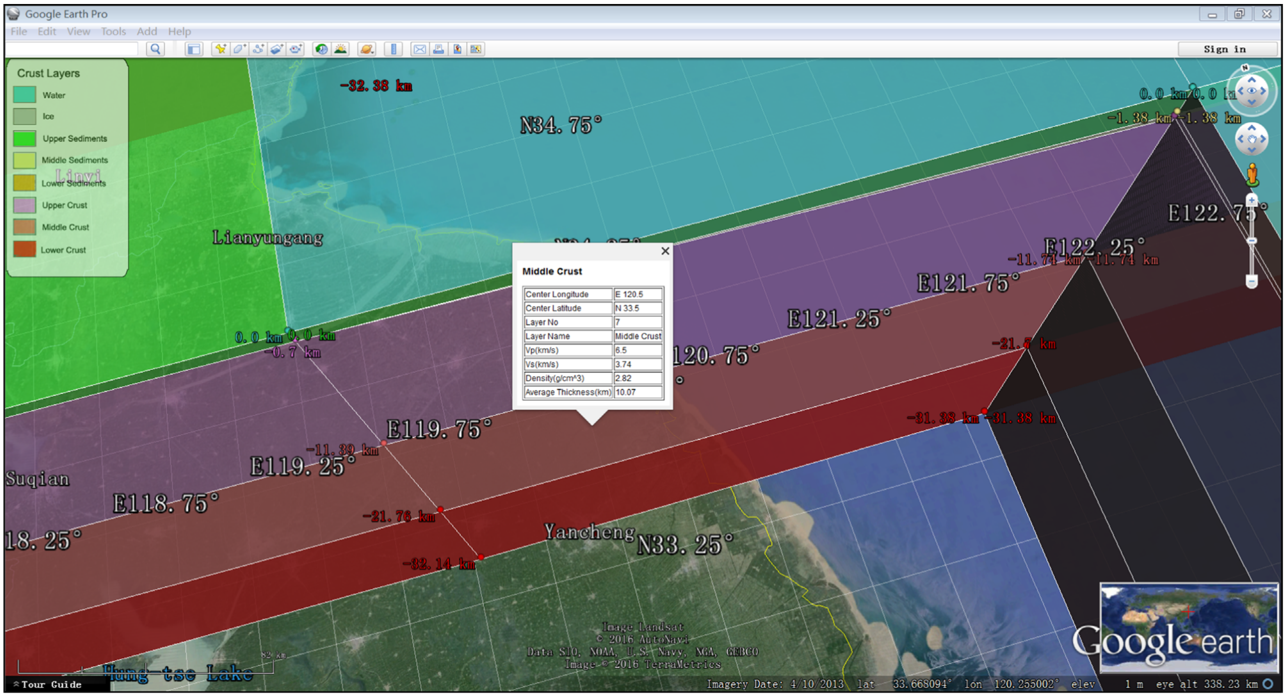

Fig. 4. Displaying the crustal models with the most detailed level (LOD2), and querying the property information associated with an interior sublayer within a crustal cell.

placemark, the property information about this cell pops up from the descriptive balloon. As the view moves even closer, the crust in LOD2 (the most detailed level) is activated, and 3D solid models representing sublayers within crustal cells appear on the screen. By default, the vertical positions of interior sublayers are elevated by 80 km in order to make them visible above the Earth's terrain surface. With advanced visualization tools embedded in Google Earth, we can freely explore 3D solid models in a variety of ways. When we click a sublayer, the property information associated with this sublayer is displayed in a descriptive balloon (Fig. 4).

To disseminate and visualize those KML-formatted crustal models on the Internet, we store the model files into a web server,

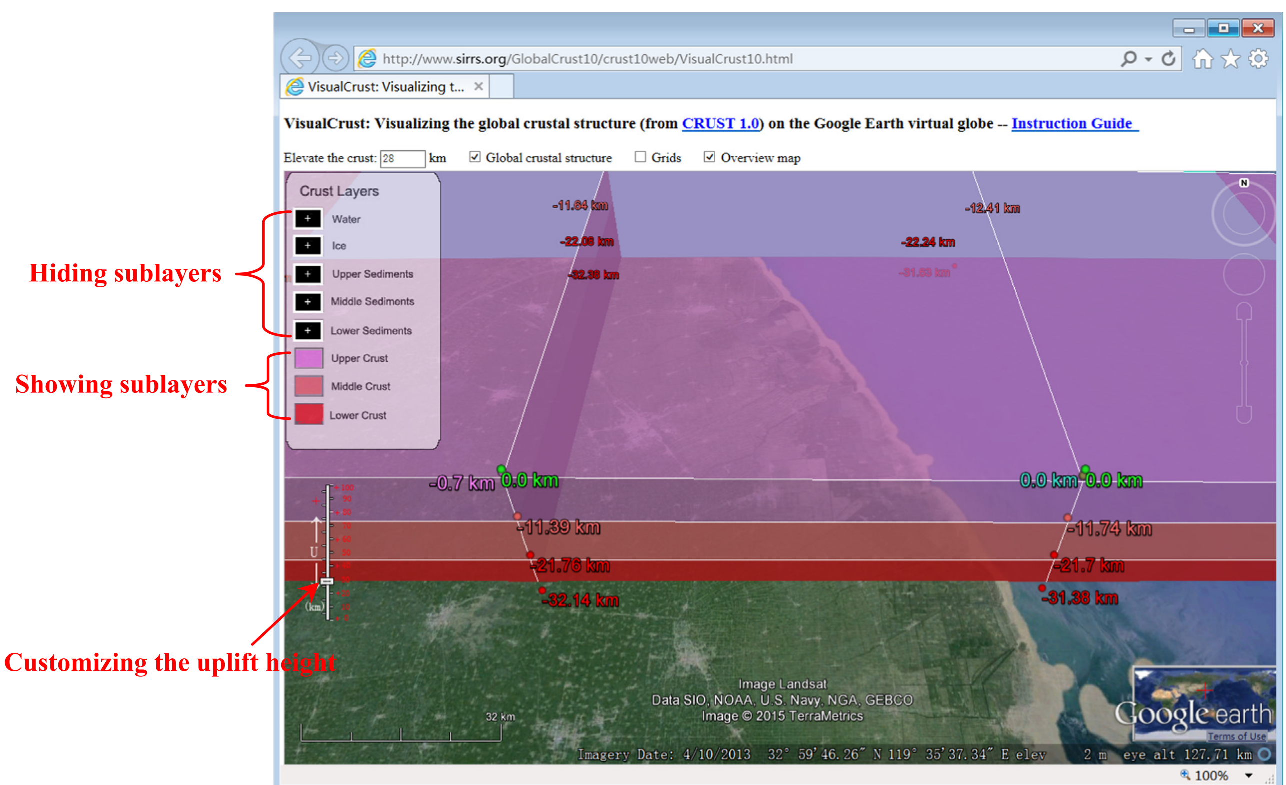

Fig. 5. Controlling the visibility of individual sublayers, and setting the uplifted height to elevate the vertical position of 3D solid models. In this figure, the top five sublayers (from water to lower sediments) have been unchecked in the legend; consequently they disappear from the view. In addition, the uplifted height is set to 28 km, which is different from the default value (80 km).

and design a web application, termed *VisualCrust* (⟨http://www.visualearth.org/globalcrust10/crust10web/visualcrust10.html⟩), using the Google Earth web browser plug-in and its JavaScript API. As shown in Fig. 5, using the vertical slider control in *VisualCrust*, users can manually set the uplifted height for elevating the vertical position of 3D solid models. Moreover, by clicking the button-styled legends, it is possible to show and hide individual sublayers within crustal cells.

At present, the implementation of *VisualCrust* is based on the Google Earth plug-in and its JavaScript API (the Google Earth API). Due to security reasons and dwindling cross-platform supports, Google decided to retire the Google Earth API (Google Inc., 2014; Dordevic and Whitmeyer, 2015; Zhu et al., 2016). However, a new version of Google Earth API is being developed, and it will be released by Google in the near future. The visualization framework and implementation methods presented in this paper are also applicable for the new Google Earth.

6. Conclusions

As convenient platforms for integrating and intercomparing the efforts of researchers from many disciplines, virtual globes are widely embraced by Earth scientists to effectively communicate their research to both other scientists and the general public (Bailey and Chen, 2011). We have presented a systematic framework to visualize and disseminate the global crustal structure on virtual globes. To demonstrate the effectiveness of the proposed framework, a KML generator was developed to automatically convert crustal information obtained from the CRUST 1.0 model into KML-formatted crustal models, and a web application was designed to disseminate and visualize those models on the Internet.

The most significant feature of the presented visualization framework and associated implementations is that they are universal and automatic. The global crustal structure represented in this paper is adequate for disseminating and visualizing on the Internet. In addition, since the proposed framework and associated implementations have strong flexibility, they can be conveniently exported to other applications to support interactively visualizing and analyzing the Earth's internal structure (such as the lithospheric lid and underlying asthenosphere) on both regional and global scales in a 3D virtual-globe environment. The widespread future use of this framework will help Earth scientists represent the structure, composition and properties of Earth's interior more easily and effectively, and make it possible to combine subsurface models together with other geospatial information for promoting geoscience research and education, and better understanding of the relationship between the interior and the surface of Earth.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2016.01.015.

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