

Article

Visualizing the Structure of the Earth's Lithosphere on the Google Earth Virtual-Globe Platform

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Abstract: While many of the current methods for representing the existing global lithospheric models are suitable for academic investigators to conduct professional geological and geophysical research, they are not suited to visualize and disseminate the lithospheric information to non-geological users (such as atmospheric scientists, educators, policy-makers, and even the general public) as they rely on dedicated computer programs or systems to read and work with the models. This shortcoming has become more obvious as more and more people from both academic and non-academic institutions struggle to understand the structure and composition of the Earth's lithosphere. Google Earth and the concomitant Keyhole Markup Language (KML) provide a universal and user-friendly platform to represent, disseminate, and visualize the existing lithospheric models. We present a systematic framework to visualize and disseminate the structure of the Earth's lithosphere on Google Earth. A KML generator is developed to convert lithospheric information derived from the global lithospheric model LITHO1.0 into KML-formatted models, and a web application is deployed to disseminate and visualize those models on the Internet. The presented framework and associated implementations can be easily exported for application to support interactively integrating and visualizing the internal structure of the Earth with a global perspective.

Keywords: virtual globe; lithospheric model; KML; 3D visualization; Google Earth

1. Introduction

The Earth's lithosphere is the rigid, mechanically strong, outermost shell of the Earth. It is of the order of 100 km thick and comprises the crust and the uppermost solid mantle [1]. Understanding the structure of the Earth's lithosphere is particularly useful because it provides a key to understanding a broad range of applications including improving whole-mantle tomography, defining and understanding crust-mantle interaction, monitoring seismicity at regional or global scales, and understanding the linkage and interaction between the atmosphere and the Earth's deep interior [2–5]. Over the years, a number of global models with various levels of detail, such as 3SMAC [6], CRUST 5.1 [2], CRUST 2.0 [7], CRUST 1.0 [8], and LITHO1.0 [5,9], have been presented to depict structural features and property parameters of all or part of the Earth's lithosphere. These models are generally in the form of computer codes and corresponding model files. In order to read and work with these models, users must delve into data formats specific to a given mission, and develop dedicated computer programs or systems for visualizing and analyzing the global lithospheric structure. For example, a dedicated software package is accompanied with 3SMAC to retrieve the information of the crust and upper mantle [6]. CRUST 5.1 [2], CRUST 2.0 [7], and CRUST 1.0 [8], respectively, provide Fortran computer codes and *xyz*-formatted model files for scientific users. The LITHO1.0 model is in its

native format, and a C++ source code, termed *access_litho* [9], is needed to extract the lithospheric information at any arbitrary location. These representations have two primary limitations. The first is the potential users. The existing representations are only feasible for academic investigators, who are typically located at universities or research institutions, to conduct professional geological and geophysical research. With increased attention paid to the deep interior of the Earth, 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 lithosphere. The above-mentioned method for representing the structure of the Earth's lithosphere becomes insufficient as it is difficult to respond to the demands drawn from these users. A second limitation is the visualization and dissemination of the models. Due to a lack of web-based support, lithospheric models expressed by the current data formats cannot be visualized and disseminated over the Internet. Therefore, it will be necessary to provide a more modern, universal, and user-friendly method to represent and visualize the existing lithospheric models.

Nowadays, the Google Earth virtual globe and the concomitant Keyhole Markup Language (KML) are providing Earth scientists with an innovative platform to represent, disseminate, and visualize geospatial information [10]. As a digital replica of the entire Earth, the Google Earth virtual globe not only offers users the capability to image, analyze, synthesize, and interpret geospatial objects on different spatial scales, but can also be regarded as a reliable platform for exploring, discovering, analyzing, exchanging, and sharing geospatial information at regional or global scales [11]. The Google Earth virtual globe is changing the way we interact with geospatial data [12]. There are a number of key benefits of using Google Earth to communicate and visualize geospatial information. In Google Earth, geospatial models can be organized as KML-formatted objects, offering the opportunity of visualizing and interacting with those models in a powerful 3D virtual environment [13]. Multidisciplinary geoscience information, such as geology [14], geophysics [15], and meteorology [16], can be overlaid and visualized simultaneously. More importantly, Google Earth is a powerful platform for communicating geospatial information to a varied and potentially non-technical audience. By visualizing different datasets on Google Earth or other comparable virtual-globe platforms [17], scientists can further cross-disciplinary studies, produce new knowledge, and promote new scientific discoveries, and the general public can get an increased comprehensive understanding of the Earth's structure, composition, and evolution.

Over the years, a number of techniques have been developed to deal with multiple types of geological and geophysical data. For example, De Paor and Whitmeyer [18] presented a method through which KML, COLLADA, and JavaScript can be used to create and visualize dynamic models of the Earth's internal structure. Postpischl *et al.* [19] utilized web technologies and Google Earth to address the problem of the standardization and visualization of seismic tomographic models and earthquake focal mechanisms datasets. In order to analyze seismic tomographic models, geochemical data for rocks and sediments, and geomagnetic field models on Google Earth, Yamagishi *et al.* [20] developed several KML (Keyhole Markup Language) generators to convert datasets of different fields of the geosciences into KML documents. Mochales and Blenkinsop [21] developed a macro-enabled Excel workbook to convert paleomagnetic datasets into KML objects, which can be visualized in virtual globes. To avoid the difficulties of subsurface rendering and touring in the Google Earth virtual globe, De Paor *et al.* [22] employed the surface of the Google Mars virtual globe to approximatively represent the Earth's core-mantle boundary. Then, 3D COLLADA solid models representing crustal and mantle features can be visualized above the virtual globe's surface. Zhu *et al.* [23] presented an automatic method for the modeling and visualization of subsurface boreholes on virtual globes. However, the existing research only concerned the representation and visualization of subsurface models within local or regional areas. Up to now there are still no readily available methods for representing the global lithospheric structure derived from the existing lithospheric models on the Google Earth virtual globe. Therefore, there is a clear need to develop a universal method for the representation, dissemination, and visualization of the global lithospheric structure on Google Earth.

This paper presents a systematic framework to represent, visualize and disseminate the location and variation of the Earth's lithosphere on the Google Earth virtual-globe platform. We adopt the recently-released global lithospheric model LITHO1.0 as the research object, and choose the Google Earth virtual globe as the visualization platform for visualizing and distributing global lithospheric information. This paper first summarizes the essentials of the LITHO1.0 model, and then presents a general framework for the representation, visualization, and dissemination of the existing global lithospheric models. The implementation program is finally described.

2. The LITHO1.0 Model

The LITHO1.0 model, first formally released by Pasyanos *et al.* [5,9], is a 1° tessellated model of the crust and uppermost mantle of the Earth, extending into the upper mantle to include the lithospheric lid and underlying asthenosphere. Based on CRUST 1.0 [8] and other similar models, LITHO1.0 incorporated more types of newly available data (including an updated crustal thickness map and a newly developed uppermost mantle) to produce a reasonable starting model of the Earth's shallow structure. Therefore, it promises to be the most detailed and widely embraced global lithospheric model in the foreseeable future.

As shown in Figure 1, LITHO1.0 is parameterized laterally by tessellated nodes, consisting of 40,962 vertices and 81,920 triangles at approximately 1° resolution [5,9]. In each triangular cell, the lithosphere is described vertically by nine geophysically identified sublayers: (1) water; (2) ice; (3) upper sediments; (4) middle sediments; (5) lower sediments; (6) upper crust; (7) middle crust; (8) lower crust; and (9) lithospheric mantle (lid). In order to make as complete a model as possible, water and ice are included in the LITHO1.0 model as the first two sublayers [2,5,9]. For each sublayer, the boundary depth and physical properties, including density ρ , compressional wave velocity V_p , shear wave velocity V_s , and seismic attenuation (Q), are explicitly specified to depict the variation of the thickness and associated properties.

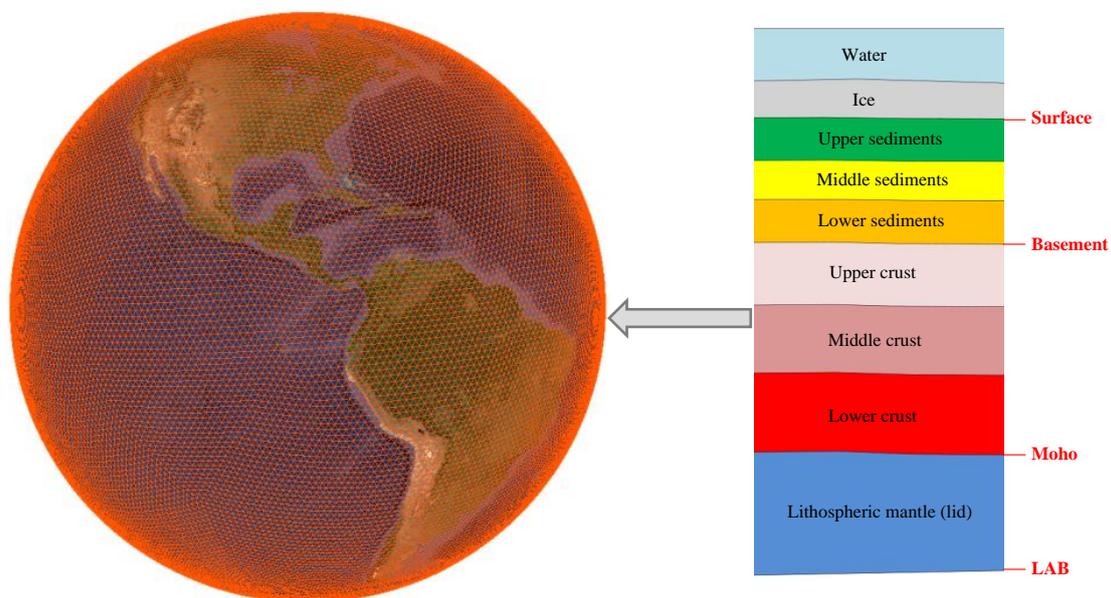


Figure 1. Lithospheric structure representation implemented in the LITHO1.0 model. The lithosphere is parametrized laterally by 40,962 tessellated nodes and 81,920 triangles at approximately 1° resolution, and vertically as nine geophysically-identified sublayers.

3. Visualization Framework

Figure 2 is a display of the visualization framework for the representation, visualization, and dissemination of the existing global lithospheric models on the Google Earth virtual globe platform.

The implementation of the proposed framework can be divided into four key steps: (1) exporting lithospheric information from LITHO1.0; (2) encoding global lithospheric models in KML format; (3) representing the global lithosphere with two scales; and (4) visualizing and disseminating the global lithospheric structure on Google Earth. The step-by-step execution is explained below.

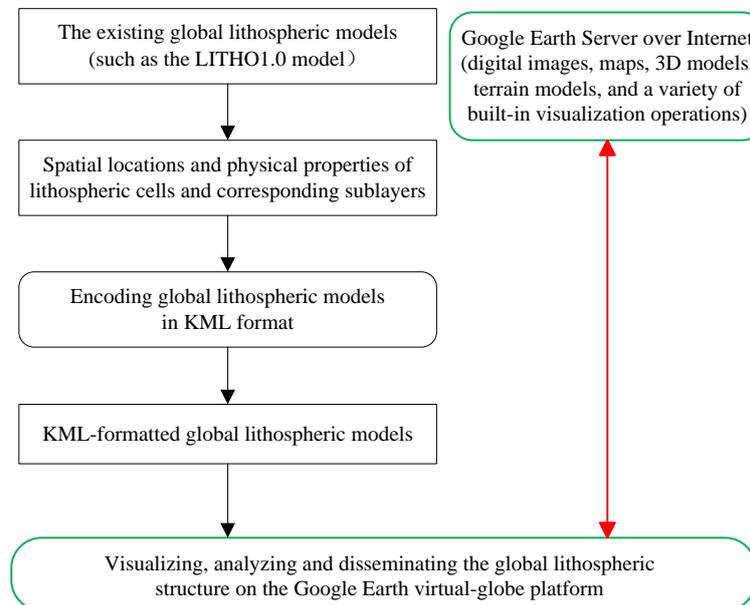


Figure 2. Overall framework for the representation, visualization, and dissemination of the structure of the Earth's lithosphere on the Google Earth virtual globe platform.

Step 1: Exporting lithospheric information from LITHO1.0. Global lithospheric information, including spatial locations and physical properties of individual lithospheric cells and corresponding sublayers, can be extracted from the LITHO1.0 model. This information will be used for subsequent digital model creation and visualization.

Step 2: Encoding global lithospheric models in KML format. According to the OpenGIS KML Encoding Standard [24,25], global lithospheric models can be encoded into KML placemarks and saved as KML files. In LITHO1.0, the lithosphere is laterally parameterized by a great deal of spherical tessellation surfaces (81,920 triangular cells). Each triangular cell can be decomposed into a series of geophysically identified sublayers along with the vertical direction. The tri-prism model can be used to represent the sublayer within a given cell. The surface of the tri-prism 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 second step, we first create individual tri-prism models to represent sublayers within a lithospheric cell, then combine all sublayers that belong to the same lithospheric cell into a KML <Document> element to represent a lithospheric cell containing multiple sublayers. In order to visualize lithospheric models situated below the Earth's surface, an uplifted height value (generally 350 km) is employed to elevate the vertical position of the lithospheric models [12,26].

Step 3: Representing the global lithosphere with two scales. The global lithospheric model is vast in data volume and complicated in geometrical structure. It is hard to simultaneously load and visualize all lithospheric cells and their sublayers on Google Earth. The level-of-detail based (LOD-based) multi-scale representation of the global lithosphere need to be implemented to improve the efficiency of visualizing the global lithospheric model. The third step is to create the global lithospheric model that can be shown in two different LODs: the simple level (LOD0) and the detailed level (LOD1). LOD0 is defined by a 2D representation of the spatial distribution for all lithospheric 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 of the Google Earth virtual globe. Since LOD0 possesses the minimal data volume with the simplest structure, it is suitable for occasions when the overview of lithospheric cells at a global scale needs to be displayed with lower resolutions. In LOD1, lithospheric cells are represented with more details because the interior sublayers of the lithosphere 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. Due to the sheer volume and complicated structure of the data, LOD1 only applies to reveal detailed information about lithospheric cells within a very limited range.

Step 4: Visualizing and disseminating the global lithospheric structure on Google Earth. The KML-formatted global lithospheric model can be loaded into Google Earth, either the stand-alone Google Earth desktop application or the web-based Google Earth plug-in [27], for 3D visualization and model dissemination. In Google Earth, 3D solid models representing interior sublayers of the lithosphere are used for visualizing and analyzing the internal structure within each lithospheric cell. Using the mouse, keyboard, and other graphical interactive devices, we can arbitrarily choose lithospheric 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 lithosphere in a more visual, intuitive, appealing, and interactive way.

4. Implementation

To implement the proposed visualization framework, we have developed a KML generator (termed *Litho2KML*) to automatically convert lithospheric information obtained from the LITHO1.0 model into KML-formatted global lithospheric models. The KML models generated from *Litho2KML* enable us to easily visualize the global lithospheric structure, including the spatial distribution of lithospheric cells and their sublayers, on Google Earth (or other comparable virtual globes) without any additional processing of the model files.

As stated in the previous section, we take four steps to convert the LITHO1.0 model into KML-formatted models using *Litho2KML*: (1) exporting lithospheric information from LITHO1.0; (2) encoding global lithospheric models in KML format; (3) representing the global lithosphere with two scales; and (4) visualizing and disseminating the global lithospheric structure on Google Earth. Global lithospheric information contained in the LITHO1.0 model can be automatically converted into KML documents via *Litho2KML*, and the KML documents can be loaded into Google Earth to represent the spatial distribution and internal properties of the Earth's lithosphere.

Litho2KML provides a simple but practical user interface to create KML documents. When the program is executed, *Litho2KML* automatically accesses the LITHO1.0 model, creates tessellated node models, triangle models, and tri-prism models for all lithospheric cells, and save these models into corresponding KML files. In addition, *Litho2KML* also creates a KML file (like *Litho 10.kml*) to construct LOD-based multi-scale representation for large numbers of lithospheric cells. When we open this KML file in the Google Earth application, global lithospheric models are automatically loaded and displayed in the 3D environment of the Google Earth virtual globe.

As shown in Figure 3, the KML-formatted lithospheric models can be loaded into Google Earth and explored with different viewpoints. When we first pan to the digital globe from very far away, the global lithosphere in LOD0 (the simple level), 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 lithospheric models with the detailed level (LOD1) are loaded automatically, and 3D solid models representing sublayers within lithospheric cells come into view (Figure 4). By default, the vertical positions of the interior sublayers are elevated by 350 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 those models with a vivid appearance in a variety of ways. When we click a sublayer, the property information associated with this sublayer is displayed in a descriptive balloon (Figure 4).

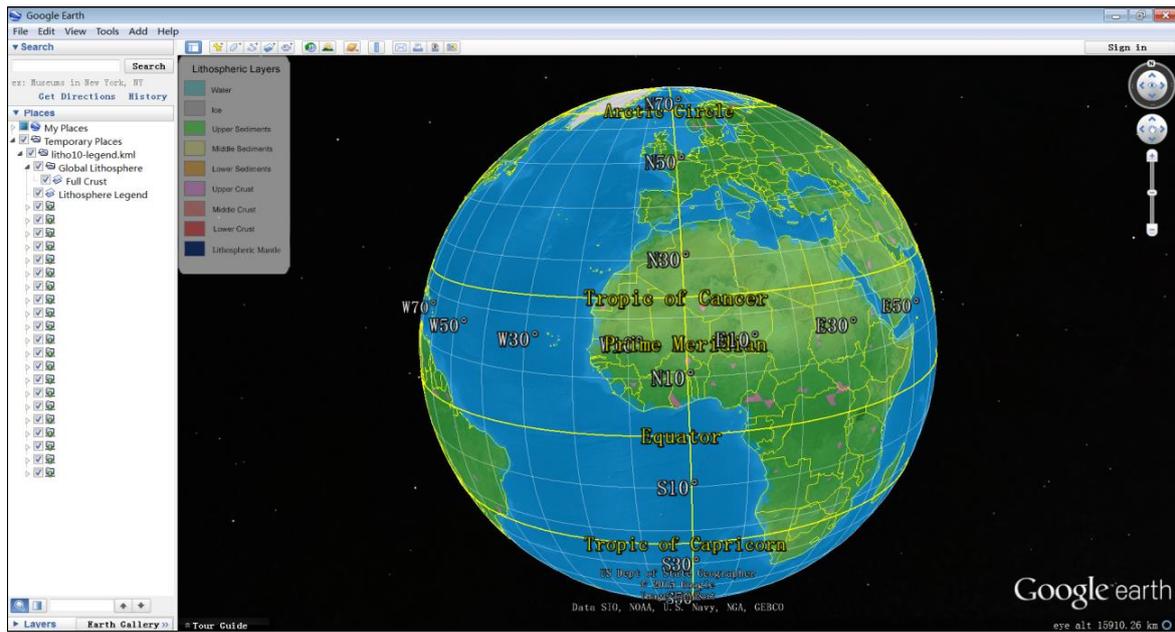


Figure 3. Displaying the global lithosphere with the simple level (LOD0) in Google Earth.

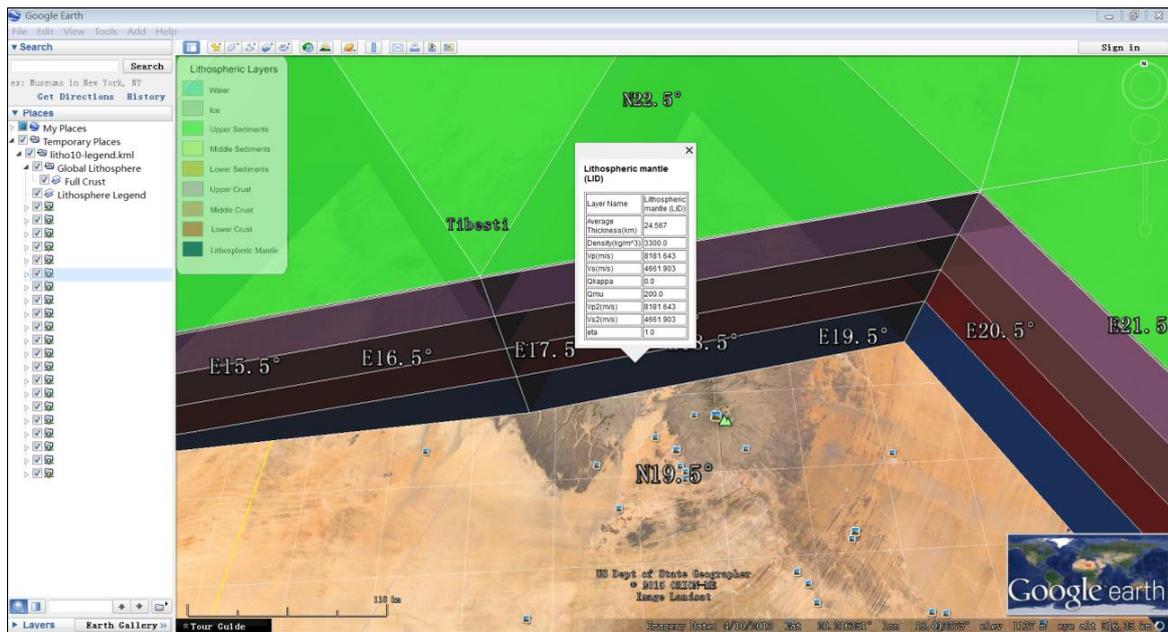


Figure 4. Displaying the lithospheric models with the detailed level, and querying the property information associated with an interior sublayer within a lithospheric cell.

We also developed a web application, termed *VisualLitho* [28], for disseminating those KML-formatted lithospheric models so that anyone may visualize the structure of the Earth’s lithosphere through the Internet. As shown in Figure 5, the user interface of *VisualLitho* is composed of two parts: (1) the view control area, which is designed for controlling the appearance and behavior of the Google Earth plug-in, is located at the top of the webpage; and (2) the Google Earth container, incorporating two screen-overlay-based custom controls (one is a group of button-styled legends, and the other is a vertical slider), is located at the bottom of the screen. The button-styled legends can be used as interactive map keys [29] to control the visibility of individual sublayers within lithospheric cells. By clicking the button-styled legends, it is possible to show and hide individual sublayers within

lithospheric cells. The vertical slider is designed to control the uplifted height value for elevating the vertical position of the lithosphere [26]. Using this control, we can manually set the uplifted height for elevating the vertical position of the 3D solid models.

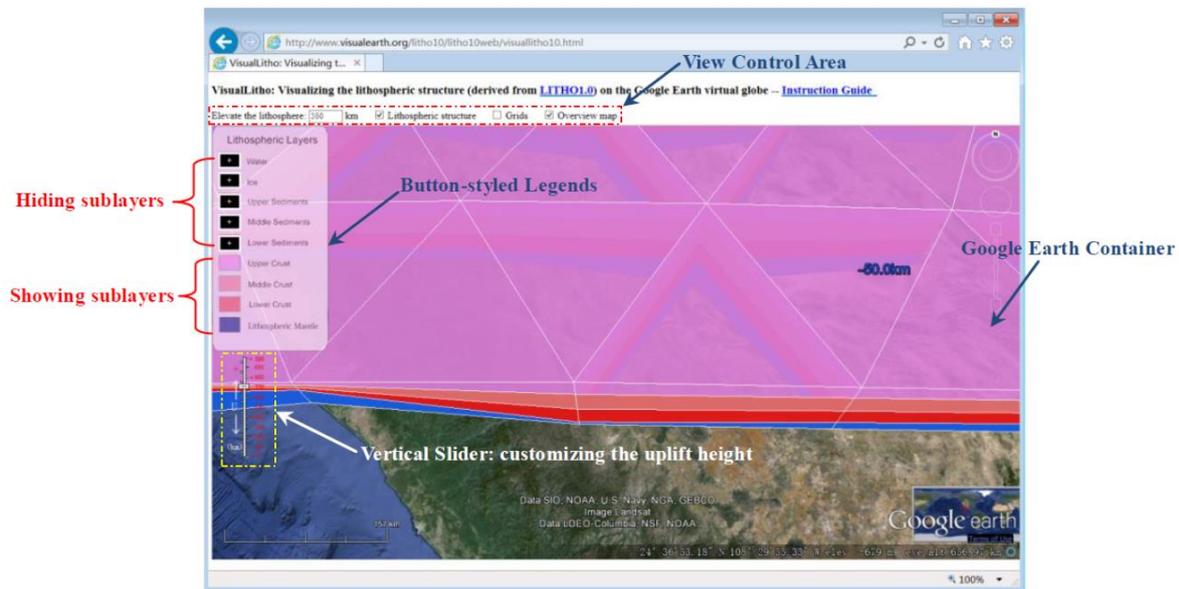


Figure 5. User interface of *VisualLitho*. In this figure, the top five sublayers (from water to lower sediments) have been unchecked in the legend; consequently they disappear from the view. In addition, the uplifted height is set to the default value (350 km).

It should be pointed out that an ArcGIS map package of the LITHO1.0 model is available on the LITHO1.0 website [9]. This package generates nine ArcGIS-formatted layers that, respectively, represent the spatial distribution of the top surface in each sublayer, and the ArcGIS-formatted layers can be easily converted into KML-formatted models by exploiting a simple script in ArcToolbox. However, the ArcGIS-formatted layers only provide the 2D representation of the spatial distribution for the top surface of each sublayer. That is, they contain neither 3D geometrical information nor physical property information within individual sublayers. This has necessitated a change in the way that global lithospheric models are displayed and interpreted, resulting in the construction of the KML-formatted models generated by *Litho2KML*. The benefit of using *Litho2KML* is that it has ability to encapsulate physical properties of geophysically identified sublayers into the 3D geometrical models. Thus, it is well-suited to produce detailed 3D lithospheric models attributed with physical properties and intuitively analyze property characteristics within each modeled triangular cell and their spatial relationships in 3D. This could dramatically improve the efficiency of exploring relationships and correlations hidden behind the complex and large volume of subsurface information, leading to an increased comprehensive understanding of the Earth's lithosphere, and maybe produce new knowledge and promote new scientific discoveries.

5. Conclusions

Google Earth is becoming a convenient platform for integrating and sharing the data and research findings of scientists from many disciplines at the global scale [11,22,30–36]. In this paper, we have designed a systematic framework to visualize and disseminate the structure of the Earth's lithosphere on Google Earth in an intuitive 3D global perspective. A KML generator is developed to automatically convert lithospheric information derived from the LITHO1.0 model into KML-formatted global lithospheric models, and a web application is deployed to disseminate and visualize those models on the Internet.

Compared with the previous methods, there are two primary advantages to the proposed visualization framework and associated implementations. The first is that the proposed visualization framework has strong flexibility. It can be conveniently exported to other applications to support interactively visualizing and analyzing the internal structure of the Earth 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 the Earth's interior more easily and effectively, and make it possible to combine subsurface models together with other geospatial data for promoting geoscience research and education, and better understanding of the relationship between the interior and the surface of the Earth. A second advantage is that lithospheric models generated from this framework are well-suited to the dissemination, integration, and visualization on the Internet. This will make lithospheric information accessible to a broad user base, and may promote the development on the societal service of geoscience information.

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