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The crustal density structures and deformation scratches in the Qinghai-Tibet Plateau

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ABSTRACT

After introducing the principals of the multi-scale scratch analysis method of regional gravity data, this paper presents the results of its application to the Qinghai-Tibet Plateau, producing three sets of density disturbance, ridge coefficient, and edge coefficient images. The density disturbance images can be used to delineate the hardness and rheological properties of continental tectonic units. The ridge coefficient images can be used to delineate deformation belts, and the edge coefficient images can be used to determine positioning boundaries of the structural division of the units. These images provide crustal geological and tectonic information from different aspects with depth information, which are able to give quantitative constrains to any possible tectonic models. To the upper crust, these results are basically coincident with surface geological and tectonic mapping. They can also provide more structural information of the middle and lower crust, which conventionally is hard to be accurately inferred. For instance, the density disturbance images show the source-zones and squeezed flows of channel flows in the lower crust, as well as the position of the subduction front of the Indian plate beneath the Himalayan mountain range. The ridge coefficient images provide the positions of suture zones, deformation and subduction volcanic belts, ancient collision belts and strike-slip zones. By combining with these edge coefficient images, one can draw out tectonic maps with different structural units in the middle and lower crust. For example, very high density terranes such as the Kashmir and Chayuhe, are divided from the Himalayan terrane, giving physical reasons for the formation of the western and eastern structural knots in the India–Eurasia collisional belt. The multi-scale scratch analysis not only provides the plane geometry of structures and deformation belts, but also their depth extension and stereoscopic patterns. For instance, a decrease of the low-density volume from the lower crust to the upper implies possible diapiric intrusions of the low-density channel flows.

1. Introduction

Previous research of the lithospheric structures and continental dynamics in the Qinghai–Tibet Plateau, a remarkable geological region in the world, have already presented tremendous significant data (Molnar and Paul, 1975; Molnar, 1988; Harrison et al., 1992; Avouac and Tapponnier, 1993; Jolivet and Hataf, 2001; Xu et al., 2009). However, current geological data is predominantly obtained from surface observations, with many of the geophysical data collected only from certain regional profiles. These data might not be sufficient for constructing three-dimensional images of crustal structure. Although seismic tomography can acquire three-dimensional images of seismic wave velocity perturbations, its spatial resolution is hardly sufficient for fine crustal imaging in the near future. Therefore, breakthroughs that reveal the three-dimensional tectonic structures in the Qinghai-Tibet Plateau will rely on the study of regional geophysical surveys. Along these lines, ground-observation gravity data with a resolution of 5 km was acquired by the China Geology Survey. As the regional gravity observations were carried out on uniform grids with accurate locations, where the regional gravity field is caused by density disturbances arising from different depths, three-dimensional crustal density structures and main deformation belts can be inferred from these data.

Over the years, with the support of the National Science Foundation of China and the China Geology Survey, we developed new methods for processing data and extracting information of potential fields. These methods include spectral analysis, multi-scale wavelet analysis, generalized inversions, and the scratch analysis methods, which can be combined into a systematic gravity data processing procedure (Fig. 1) for depicting three-dimensional crustal structures and deformation features. This new data processing set is called the multi-scale scratch analysis method. First, this data processing system uses the spectral analysis to determine if the regional gravity data can be decomposed into several sub-datasets and how many equivalent layers should be decomposed. Then, it uses the multi-scale wavelet analysis to decompose the regional

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gravity data into sub-anomalies according to different sources' depths which correspond to the desired equivalent layers. Next, the system inverses the density perturbation of each equivalent layer by using a generalized linear inversion. Finally, characteristics of the deformation belts in each equivalent layer are extracted using the scratch analysis method.

The multi-scale scratch analysis method is systematic and sophisticated, and in this work it has been applied to regional gravity data to extract information about deformation belts in the Qinghai-Tibet Plateau. Our analysis has revealed variations of the deformation belts and plane distribution features from the upper crust to the lower crust, and it provides new information for the study of the lithosphere that could not be obtained by surface geology. Our previous papers introduced the method of multi-scale scratch analysis and its applications (Yang et al., 2015a,b). In this paper, we focus on its application to the Qinghai-Tibet Plateau, show the revealed crustal density structures and deformation belts, and discuss the geological and tectonic implications of the resulting maps.

The main scientific issues discussed in this paper include: what are the differences between tectonic features in the upper, middle and lower crust? Do they present any new information that is significant to continental dynamics in the studied area? The multi-scale scratch analysis produces three sets of images (density disturbance, ridge coefficient, and edge coefficient images), which contain a wealth of information. Do these resulting maps have any relationships with their surface geology? These issues will be discussed in detail as follows.

2. Brief introduction to the multi-scale scratch analysis

In previous papers (Yang et al., 2015a, 2015b), we use the regional gravity field in the Qinghai-Tibet Plateau as an example to introduce the method of the multi-scale scratch analysis, including spectral analysis for defining the equivalent density layers and estimating depth of the layers, decomposition of the gravity field using the multi-scale wavelet analysis, density inversion of decomposed gravity anomalies, and scratch analysis for locating deformation belts.

The multi-scale wavelet analysis of regional gravity field is based on the scale-depth law that a gravity anomaly generated by a single source body has the characteristic scale. The deeper the source locates, the larger the characteristic scale is. In addition, the characteristic scale of a surface Bourger gravity anomaly is approximately proportional to buried depth of the source (Hou and Yang, 1997, 2011). When it comes to gravity anomalies superimposed by multiple source bodies, they no longer have the characteristic scale. The multi-scale wavelet analysis utilizes the characteristic scale to recover the characteristic scale in the ground superimposed anomalies, and decomposes them with different scales, making the decomposed wavelet details obtain characteristic scales again (Mallat, 1989; Hou and Yang, 1997). Thus the multi-scale wavelet analysis can delineate crustal density structures on equivalent layers at different depths.

Depth of each equivalent layer can be calculated using the depth equation of gravity wavelet details, which are based on potential field theory in the wavenumber domain (Bhimasankakam et al., 1977; Yang et al., 1978). For a single source body, slope of the logarithmic power spectrum of its gravity anomaly is proportional to the source's buried depth. Accordingly, recognizable straight segments with different dipping slopes in spectral curves indicate buried depths of density disturbances corresponding to different equivalent layers. The steeper the straight segment in the power spectrum is, the deeper the equivalent layer is buried. In other words, if there appear a certain amount of recognizable straight segments with different slopes, the regional gravity field can be decomposed into sub-anomalous sets by applying the multi-scale wavelets analysis. In addition, the average depth of each sources' equivalent layer can be computed by using the depth equation to the decomposed wavelet details. After decomposing gravity anomalies with discrete wavelet transformation and computing the average depth of each equivalent layer, we should inverse the density disturbances using the generalized linear inversion method (Yang, 1987, 1997).

From physical point of view, crustal deformation belts can be regarded as scratches in the crust caused by past dynamic processes, causing strip-like rock densities anomalies in some narrow belts that are called ridge-like scratches. The typical feature of the crustal scratches in the density disturbances are linear shape with high anisotropic parameters. Furthermore, the long ridge-like density anomalous belts in the crust also cause linear scratches in regional gravity field, characterized by rapidly changing gravity gradients, strong anisotropy, and directionally stable anisotropy. These characteristic parameters are implicit in the second order spectral moment of the local gravity field. Based on the second spectral moments, we can calculate an integrated parameter, called the ridge coefficient, to locate the crustal deformation belts (Sun and Yang, 2014; Yang et al., 2015a). The ridge coefficient Λ mainly expresses the density anisotropy: $\Lambda = 0$ implies no ridge-like scratches around the local cells; while $\Lambda = 1$ indicates

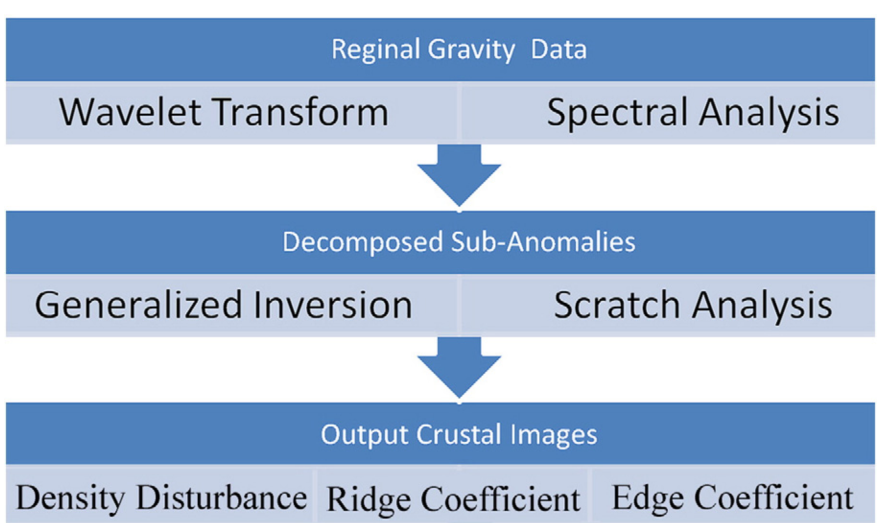

Fig. 1. Flow-chart of the multi-scale scratch analysis of regional gravity data processing of the Qinghai-Tibet Plateau.