Continental margin in South China: Multidisciplinary frontiers in neutrino geoscience

21st-23rd July 2017

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Workshop Goals: Bring together those interested in understanding the 4D geology of South China, including the adjacent South China Sea.

1 Introduction

Please read and consider

A fundamental goal of this workshop is to help both the Chinese and International geological community to get ready for the geoneutrino result from the JUNO experiment. The particle physicists in a few years will present us with a geoneutrino flux measurement for South China. We need to establish a hypothesis and test it. The JUNO experiment offers us a paramount opportunity to *build a quantitative 3D model that describes the physical and chemical nature of this lithosphere*, describing the abundance and distribution of the heat producing elements. From that we can calculate the geoneutrino flux with a very small uncertainty and thus we have a model results in hand ***before*** the physicists make their measurement. The important questions are:

- How do your insights and presentation enhance the goals of the workshop?
- What fundamental geological, geochemical and geophysical data are needed to address to scientific goal for constructing and testing a model of the South China lithosphere?
- It has been proposed (Gao et al., 2009; see below) that the crust of Eastern China is distinctly different from a global average continental crust.* Do you agree? If not, what can be done to improve upon this model and update it?
- How would you construct and test this quantitative 3D model? One could start with a 1° x 1° x 5 km voxel-ated lithosphere for all of Eastern China and surroundings and assign physical and chemical attributes to each voxel.
- How can we use a well constrained 3D model of this lithosphere to predict its response to future tectonic forces, predict depths of earthquakes, identify natural resources for societal use and present it as a template for building other 3D models elsewhere?

*"However, our estimates of heat-producing elements K, Th, and U, and thus the value of heat production are significantly lower than those of Wedepohl (Table 4). As stated above, both the observed and corrected mean crustal velocities of East China are 0.2 - 0.3 km s^{-1} slower than the global continental crust. As a result, a more felsic composition is in accordance with geophysical data."
Quote from: Gao, S. et al. (1998) Chemical composition of the continental crust as revealed by studies in East China, *Geochimica et Cosmochimica Acta*, Vol. 62, No. 11, pp. 1959-1975

As our understanding for the lithosphere of South China matures we will develop a 4D model of its geological evolution. Understanding the 4D evolution of this continental margin contributes to understanding and identifying locations and origins of economic resources in the region. Is South China a volcanic or nonvolcanic margin (see Mooney abstract)? Flat slab, stagnant slab, and slab roll back are other topics being considered (see Liu, Niu, Zhong, etc), with the understanding that all of these conditions might apply over the last 250 million year.

The following pages has the Abstracts followed by a Method for predicting a geoneutrino signal at a detector, which is a brief description of building a 3D physical and chemical description of the lithosphere that accurately and precisely predicting the flux of geoneutrinos at a detector based on integrating as much geology, geophysics and geochemistry in the area surrounding the detector (generally the first 500 km).

2 Abstract Volume

Table 1: Author and title of Speaker abstracts

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Thermo-chemical heterogeneity of lithosphere

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Lithosphere forms the outer 100-300 km thick shell of the Earth. The study of the continental lithosphere offers the only possibility to decipher the Earth's history over the past ∼4.0 billion years, since the oceanic lithosphere is recycled into the mantle on a 200 Ma scale. Detailed information on lithosphere structure, composition and secular evolution is pivotal for understanding many of the processes in the Earth's interior, since lithosphere behaves as thermal boundary layer on top of convecting mantle, as chemical boundary layer formed by mantle melting and extraction of light material to shallow levels, and as mechanical boundary layer which participates in plate tectonic processes and deformation. Properties of all three boundary layers, including their thickness, are essentially controlled by temperature.

No understanding of lithosphere evolution is possible without a detailed knowledge on its structure and physical properties. They are reflected in lateral and vertical variations of different physical parameters, which are typically measured in remote geophysical surveys. These parameters strongly depend on temperature, composition, and physical state of the matter. Importantly, temperature variations mask compositional anomalies in seismic and gravity data. Therefore, lateral and vertical structural heterogeneities within the continental lithosphere are poorly constrained. As a result, lithospheric models derived from different geophysical techniques are often inconsistent and non-unique. It necessitates a join interpretation of the entire set of data provided by different techniques used in Earth sciences, where thermal studies play a critical role because of a strong temperature-dependence of major parameters controlling processes win the lithosphere (seismic velocities, density, viscosity, etc).

The presentation summarizes geophysical models for ancient continental lithosphere (Precambrian cratons), with focus on thermo-compositional heterogeneity of the lithospheric mantle as constrained by a set of different geophysical data. The latter include (i) thermal structure of the Precambrian lithosphere based on surface heat flow data, (ii) lithosphere density heterogeneity as constrained by isostasy and satellite gravity data, and (iii) non-thermal part of upper mantle seismic velocity heterogeneity based on a joint analysis of thermal and seismic tomography data. The results demonstrate that the lateral extent of ancient cratonic lithospheric keels diminishes with depth and is significantly smaller than geological boundaries of the cratons exposed at the surface. A comparison of density structure of the cratonic lithosphere with surface tectonics indicates a significant correlation between the deep, shallow, and near-surface structure of the lithosphere. The conclusions are illustrated by examples from different cratons. Lateral and vertical heterogeneity of the cratonic lithosphere is discussed in connection to regional tectono-thermal evolution.

Crustal heat generation from a global geochemical and seismological perspective

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Aside from geoneutrinos, there is no surface-based geophysical observation that directly relates to internal heat production. Surface heat flow can be used to estimate heat production, but requires assumptions about the heat budget. Several techniques may be used to estimate temperature, and thereby infer heat production, but are in general highly non-unique. By using a global geochemical dataset with >200,000 chemical analyses, we are able to estimate several physical properties, including heat production and seismic velocity for a wide variety of rock types. We find that average heat production and seismic velocity are linearly correlated both globally and for many geological provinces. By combining global crustal seismic models, we are able to produce a vertical estimate of lithospheric heat production that when combined with aforementioned techniques greatly improve our estimates of global heat loss.

Geological Evolution of the South China Craton

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This presentation is an overview of the geological history of South China. South China is geologically an ancient piece of continent, called the South China Craton (SCC). The SCC was formed by collision and amalgamation of two continental terranes: the older (<3.0 Ga) Yangtze block in the west and the younger (>2.0 Ga) Cathaysia block in the east. The timing of the collision, hence the age of the SCC, has been controversial. Most researchers think that the Yangtze-Cathaysia collision occurred in the Neoproterozoic (∼1.0 Ga), during the assemblage of the super continent Rodinia. However, some recent studies have suggested that this collision occurred earlier, during the Paleoproterozoic (∼1.8 Ga), and have related the SCC to the formation of the super continent Columbia. Nonetheless, since the Yangtze-Cathaysia collision, the SCC has behaved as a relatively coherent block in the subsequent geological evolution, albeit with major differences between the Yangtze and the Cathaysia blocks. One major geological development of the SCC during the Phanerozoic (<570 Ma) is magma intrusion and eruption, which peaked in the Mesozoic (∼70-200 Ma), forming the largest granite province in the world with rich metallic ore-deposits. The cause of such large-scale magmatism remains uncertain. In the Cenozoic (<65 Ma) the rest of continental China has been tectonically active due to the India-Eurasian continental collision that raised the Tibetan Plateau; the SCC, on the other hand, has been tectonically quiescent, showing little deformation, volcanism, and seismicity.

Flat-slab subduction and tearing within the transition zone in the East Asian continental margin

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The present-day subducted slab architecture in the mantle is the record of plate tectonics in the geological time. The spatial configuration of slabs interpreted from tomography help open another window for us to understand the earth's past. In the East Asia continental margin, a flat-slab within the transition zone is clearly shown as high velocity anomaly in the tomography models. This slab has been

interpreted to be a continuous wide slab for a long time, but in fact it was segmented. How, when, and which slab subducted to the transition zone, and how the slab was torn, still have not be clarified. One of the primary reasons is unsuitable interpretation of the Philippines sea plate kinematics and evolution because of the poor constraints. Here, we implements a "deep-time" reconstruction of the Philippines sea plate and western Pacific plate subduction in the East Asian continental margin since 50 Ma based on the local geological records, geophysical observation, and the existing available reconstructions. This reconstruction demonstrates a NNE-oriented wedging of the Philippines sea plate and NNE-oriented migration of TTT triple-junction within the Pacific Plate from 36-6 Ma. The 4D mantle convection assimilation by using our reconstructed plate model predicts the present-day slab architecture that fits the geological and geophysical constraints. Our work suggests that the flat-slab within the transition zone derives from the subduction of western Pacific Plate beneath East Asia since Eocene, the NNE-oriented wedging of the Philippine Sea plate lead to the tearing of the Pacific slab and the migration of the TTT triple junction since late Oligocene, and the north westward low-angle subduction of young Shikoku Basin within the Philippines sea plate might have induced to form the highly-deformed slab beneath Southwest Japan. Clearly, our results have comprehensive implication for the understanding of East Asia and western Pacific plate tectonic history and mantle geodynamics.

Using geoneutrinos to constrain the Earth's composition and its heat production

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Geoneutrinos, naturally produced electron anti-neutrinos, are generated during beta decays of radioactive isotopes in the Earth. They are a unique direct probe of our planet's interior. Neutrino geophysics is an emerging field in the geosciences; it has only recently completed its first decade of data taking. Detectors in Japan (1 kTon, KamLAND) and Italy (0.3 kTon, Borexino) have been counting for some time now and these will soon be joined by SNO+ (1 kton, expected to be counting in 2017) in Sudbury, Canada; JUNO (20 kton, expected to be counting in 2020) in Jiangmen, China; and Jinping (3 kton, expected to be counting in 2022) in Mianning County, Sichuan Province, China.

The annual geoneutrino count rate at these detectors is low: KamLAND is 14 events/year and Borexino is 4.2. The predicted rates for SNO+ is 20, JUNO is 400, and Jinping is 100 events per year. Approximately 20% of the signal comes from Th and 80% from U. Thus, the total exposure time is significant for these experiments, as measurement uncertainties follow Poisson's statistics (Šrámek et al., 2016). Differences in count rates vary according to detector size, detector efficiency, and geologic setting.

The detectors are kTon in scale, deep underground, and are liquid scintillation instruments. Their position underground shields them for the cosmic ray produced moun showers, which are a significant background for these detectors. The measured flux of geoneutrino reveal the amount of radiogenic heat from the decay of Th and U (only detectable signal). To date these results constrain the Earth's contribution from radiogenic heating between 25% and 70% of the Earth's present-day power (46 $\pm$ 3 TW). Geoneutrino studies are providing quantitative constraints of the amount of uranium and thorium inside the Earth. Knowing precisely the absolute U and Th content of the Earth defines the planet's nuclear power budget for the heat producing elements. It also explicitly defines the absolute abundances of the refractory elements in the planet, which in turn specifies the mode proportion of Ca-pervoskite in the lower mantle. The power of geoneutrino studies is in specifying the amount and distribution of heat producing elements in the continents.

I will report on the latest data from geoenutrino studies and the data expected to be obtained over the next 8 years. These data will critically evaluate competing models of the bulk silicate Earth (i.e.,low, medium, and high Q models, respectively, 10, 20, and 30 (ng/g) U, Th/U = 4, and K/U =1.4 x10^4) and exclude some at the 1-sigma level. By 2025 there are projected to be 5 detectors counting the Earth's flux of geoneutrinos (10^{25} s^{-1}); each will define locally the radiogenic power in the immediate (500 km) crust and collectively, the global array of detectors will define the residual radiogenic power left in the mantle and the Earth's Th/U value. Ongoing studies presently reveal that the Earth's Th/U value is 3.9 $\pm$ 0.15, a value coincident with that of the solar system. Consequently, given the marked differences in the partitioning behavior of Th and U between metal and silicate, this well constrained Th/U value for the bulk silicate Earth documents that negligible Th and U is in the core. Geoneutrino studies provide critical constraints on the power driving plate tectonics, mantle convection, and the geodynamo.

Šrámek, O., Roskovec, B. Wipperfurth, S.A., Xi, Y., and McDonough, W.F. (2016) Revealing the Earth's mantle from the tallest mountains using the Jinping Neutrino Experiment, *Scientific Reports, Nature*, 6, Article number: 33034 doi:10.1038/srep33034

Structure, composition and evolution of the continental margins, with an emphasis on China

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Passive continental margins are boundaries between oceanic and continental regions where neither collisional deformation nor subduction is taking place. Despite their present-day tectonic quiescence, the crustal structure of passive continental margins is diverse and complex since they are formed by continental rifting that accompanies the breakup of a super-continent, such as Pangea (200 Ma.) or Rhodinia (1.0 Ga). Prominent examples include the eastern seaboard of North America, the Gulf Coast, the coasts of Antarctica, and the east, west, and south coasts of Africa, and the South China margin. Tectonic activity is minimal and erosional or weathering processes dominate, forming low-relief geography and ample sedimentary deposits. These sedimentary basins are economically and scientifically valuable due to their large reservoirs of hydrocarbon and their recorded history of the rifting between two continents. Passive margins may be divided into two primary types; volcanic margins and nonvolcanic margins. The North Atlantic Margin, formed during early Tertiary lithospheric extension between Europe and Greenland, involving the Iceland hot spot, and is one of the world's largest volcanic margins. The US Atlantic volcanic margin was formed in the Mesozoic, but apparently without the involvement of a hot spot. The extensive volcanic rocks of these margins were formed by excess melting associated within a wide, hot zone of asthenospheric upwelling present during rifting. In many cases a high-seismic velocity (7.3 km/s) lower crust is also present. Nonvolcanic passive margins are formed where asthenospheric temperatures remain lower during rifting. An example is the non-volcanic margin of the Laborador Sea of northeastern Canada. The first detailed marine measurements of the crustal structure of the South China margin were made in 1993. At present six high-quality deep seismic profiles recorded with ocean-bottom seismometers are available in the South China Sea. In general terms, the crust thins from about 30 km at the coast to 12 km thickness (oceanic crust) over a distance of 200-300 km. A high-velocity (>7.0 km/s) lower crustal layer exists beneath some of these profiles, but the origin of this layer is highly controversial. The three competing models for the origin of this high-velocity layer are: (1) an island arc; (2) magmatism during super-continent break-up, and (3) magmatism during Cenozoic extension. I discuss each of these models for the evolution of the South China margin.

Chinese continental shelf of exotic origin collided with continental China 100 million years ago

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It has been axiomatically accepted that the basement of a continental shelf is the offshore extension and geologically part of the same continental lithosphere. While this notion may hold true in places, our analysis of the distribution of Jurassic-Cretaceous granitoids throughout the entire eastern continental China in space and time led us to the conclusion that the basement of the Chinese continental shelf (beneath East China Sea and South China Sea) is of exotic origin geologically unrelated to the continental lithosphere of eastern China [1]. This exotic terrane of a sizeable mass with large compositional buoyancy could be an oceanic plateau, but more likely a micro continent, which was transported by (and along with) the paleo-Pacific plate moving in the course of NW direction and subducting beneath the eastern margin of the continental China in the Mesozoic, responsible for the granitoids with emplacement ages of ∼190 Ma to ∼90 Ma. The termination of the granitoid magmatism throughout the vast region at ∼90 Ma manifests the likelihood of subduction cessation at this time or more shortly beforehand, probably at ∼100 Ma. Subduction stops only if the trench is jammed by a sizable terrane that is compositionally buoyant and physically unsubductable. The basement of the Chinese continental shelf is understood to be such an unsubductable mass as said above that collided with the eastern margin of the continental China and jammed the trench at ∼100 Ma. The locus (or "suture") of the jammed trench at ∼100 Ma is predicted to locate on the Chinese continental shelf in the vicinity of, and parallel to, the Southeast coastal line. The curved arc-shape of the coastal line is inherited from the pre-100 Ma arc-shaped trench.

To locate the locus in the northern section in the East China Sea and Yellow Sea is not straightforward given this region was not affected by the exotic microcontinent in the south and due to the recent (<20 Ma) tectonic re-organization associated with the opening of the Sea of Japan and Yellow Sea [2].

The trench jam at ~100 Ma led to the Pacific plate to change its course of motion from NW to NNW and to subduct beneath the predecessors of the Kamchatka and western Aleutian trenches as manifested by the age progressive Emperor Seamount Chain of the Hawaiian hotspot origin. This Pacific plate re-orientation produced a transform boundary between the NNW moving Pacific plate and the newly accreted eastern Asian continental plate. To the north of the transform (north of the East China Sea), the prior subduction became oblique subduction, explaining volumetrically small younger granitoid magmatism in the Korean Peninsula and Southwest Japan (as young as ~71 Ma) and Russian Far East (as young as ~56 Ma) [2].

The eastern continental China in the Mesozoic can be interpreted as an active continental margin, but NOT an Andean-Type margin as treated by many. This is because the granitoids do not define "magmatic arcs" at any given time, but distribute randomly in space and time in a wide zone in excess of >1000 km. This observation indicates the likelihood of the presence of a stagnant paleo-Pacific slab in the mantle transition-zone beneath the region as is the case in the Cenozoic, which is seismically observed at present. The c slab under heating by the ambience above and below caused the slab dehydration. This dehydration caused a sequence of processes of geodynamic and geological significance. The released water facilitated the formation of hydrous melt within and above the transition zone, which percolated through and metasomatized the upper mantle, weakened the base of the lithosphere and transformed it into asthenosphere, hence having thinned lithosphere in the Mesozoic, accompanied by melting of the being-converted "lithospheric material" to produce basaltic melt as the heat source for crustal melting and the granitoid magmatism. Such within plate magmatism was ultimately triggered by subduction and subducted slabs, and can be readily understood as a special (vs. plate boundary zone) consequence of plate tectonics [3].

This new understanding on the origin of the Chinese continental shelf introduces an innovative hypothesis for consideration and testing. Basement penetration drilling on ideal sites of the shelf in collaboration with industries and IODP offers the most effective testing towards a genuine understanding of the tectonic evolution of the greater western Pacific since the Mesozoic in a global tectonic context.

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Overview of Current Geoneutrino Measurements and Their Impact on Geoscience

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We discuss current measurements of geoneutrino flux done by KamLAND and BOREXINO experiments. We stress the importance of KamLAND, which was the first to measure geoneutrino flux, and set the benchmark for all future experiments. The impact of such an achievement on the geoscience and particle physics will be discussed. Finally, we mention issues which cannot be resolved by these experiments due to the uncertainty of the measurement.

Geological models for geoneutrino prediction at JUNO: uncertainties and weak points

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Measurements of the Earth's flux of geoneutrinos reveal the amount of uranium and thorium in the Earth and set limits on the amount of radiogenic power in the planet. Comparison of the total geoneu-

trino flux measured at large underground neutrino experiments with geologically informed predictions of geoneutrino emission from the crust defines the radiogenic power in the convecting mantle.

The current geoneutrino detecting experiments, KamLAND in Japan and Borexino in Italy, will by year $\sim$ 2020 be supplemented with three more experiments: SNO+ in Canada, and JUNO and Jinping in China. We predict the geoneutrino flux at all experimental sites including detailed discussion of JUNO site. The combination of data from all experiments is expected to provide tight limits on radiogenic power in the Earth's mantle. We further discuss how the geoneutrino measurements at the three relatively near-lying (≤ 3000 km) detectors KamLAND, JUNO, and Jinping may be harnessed to improve the regional model of the lithosphere.

Several issues in geological models of geoneutrino flux prediction from the crust must be addressed in order to benefit from the neutrino physics measurements: 1. Available models of crustal structure (CRUST2.0, CRUST1.0, LITHO1.0) differ in the total mass of the crust and consequently, in combination with a compositional estimate of Th and U abundances, predict different crustal radiogenic heat production and geoneutrino flux. 2. Models of crustal structure lack an uncertainty estimate. This prevents a rigorous determination of the mantle geoneutrino flux. 3. Global models of crustal structure and chemistry are too coarse to provide a realistic prediction of geoneutrino flux from nearby crust. Studies of local geology have been performed around KamLAND, Borexino and SNO+ experiment site. Dedicated studies of crustal geology must be performed around the two experiment sites in China. 4. The relative uncertainty of physics measurement of total geoneutrino flux is expected to decrease below the uncertainty of geological prediction of crustal flux. The inference of mantle radiogenic heat production will therefore be limited by how well Earth science can characterize the crust near the detector sites.

Tracing subduction zone processes by using Mg isotopes

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The key component during subduction is the subducting oceanic slab including marine sediments, altered basalts, abyssal peridotites and fresh mafic and ultramafic rocks. How these rocks interact with each other and the mantle wedge at elevated temperature and pressure during subduction controls the subduction zone processes such as earthquakes and volcano eruptions. The nature, behavior and fate of subducting materials however are still not well understood. For example, many simple but important questions are still highly debated: 1) the components and origins of the fluids in the subduction zone and their implications on arc magmatism and seismicity; 2) the contribution and mechanisms of subducted sediments and altered basalts to arc magmatism; 3) the interactions between different types of rocks/fluids among the subducting slabs and how they affect the outputs of the subduction zone; 4) the differentiation and evolution of the arc crust and their relationship to the origins of the continental crust; 5) the roles of subducted materials in producing the mantle heterogeneity; 6) the global elemental cycling and long-term climate change, including the deep time evolution, carbo recycling etc. Answering these questions require extensive, comprehensive studies of rocks and minerals at subduction zone by using all kinds of tools such as field studies, laboratory (high-T and high-P or hydrothermal) experimental studies, thermodynamic calculations, petrological and petrographic examinations, geochemical and isotopic analyses etc. In this talk, I will describe how Mg isotopes can be used to answer some of these questions and provide insights into subduction zone processes and geoneutrino studies.

Perceiving the crust in 3D: a model integrating geological, geochemical, and geophysical data

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Regional characterization of the continental crust has classically been performed through either geologic mapping, geochemical sampling, or geophysical surveys. Rarely are these techniques fully integrated, due to limits of data coverage, quality, and/or incompatible datasets. We combine geologic observations, geochemical sampling, and geophysical surveys to create a coherent 3D geologic model of a 50×50 km upper crustal region surrounding the Sudbury Neutrino Observatory (SNO) in Canada, which includes, the Southern Province, the Superior Province, the Sudbury Structure and the Grenville Front Tectonic Zone. Nine representative, aggregate units, of exposed lithologies, are geologically characterized, geophysically constrained, and probed with 112 rock samples. A detailed study of the lognormal distributions of U and Th abundances and of their correlation permits a bivariate analysis for a robust treatment of the uncertainties. A downloadable 3D numerical model of U and Th distribution, defines an average heat production of $1.5^{+1.4}_{-0.7}$ μW/m3, and predicts a contribution of $7.8^{+8.4}_{-3.2}$ TNU (a Terrestrial Neutrino Unit is one geoneutrino event per 10^{32} target protons per year) out of a crustal geoneutrino signal of $31.2^{+8.6}_{-4.7}$ TNU. The relatively high local crust geoneutrino signal together with its large variability strongly restrict the SNO+ capability of experimentally discriminating among BSE compositional models of the mantle. Future work to constrain the crustal heat production and the geoneutrino signal at SNO+ will be inefficient without more detailed geophysical characterization of the 3D structure of the heterogeneous Huronian Supergroup, which contributes the largest uncertainty to the calculation.

The post-Jurassic tectonic and geodynamic evolution of Southeast Asia

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The tectonic evolution of East and Southeast Asia has been shaped by the long-term convergence of the Eurasian, Indo-Australian and (proto) Pacific plates since the breakup of the Pangea supercontinent. This prolonged subduction history resulted in multiple phases of back-arc opening and closure, leading to oscillations between intra-oceanic and Andean-style active margins. The complex convergence of tectonic plates created a mosaic of exotic terranes, ophiolite belts and suture zones that are often associated with mineral and hydrocarbon resources. We synthesised marine and continental geological and geophysical data to construct a regionally-refined plate tectonic reconstruction in the community software, GPlates (www.gplates.org). These plate motion histories are then used as surface boundary conditions for global forward models of mantle convection using CitcomS. The predictions of mantle structure are then qualitatively compared to a suite of P- and S-wave seismic tomography models. The data and our models suggest that the East Asian margin underwent a major switch from Andean-style subduction to one dominated by slab roll-back and back-arc opening in the Late Cretaceous. We argue that the Proto South China Sea opened at this time as a back-arc, and detached a small continental fragment (Semitau) from the South China Margin, much like the opening of the Tyrrhenian Sea and the Sea of Japan. The continued opening of this back-arc was interrupted when Semitau collided with northern Borneo in the Eocene (~50 Ma), leading to the accretion of Semitau and the subduction polarity reversal. South-dipping subduction of the Proto South China Sea led to rifting of the Dangerous Grounds and northern Palawan continental blocks, passive margin formation on the South China margin, and seafloor spreading in the successor South China Sea basin from ~32 Ma. These continental blocks collided with northern Borneo by ~15 Ma, resulting in the choking of subduction and the abandonment of seafloor spreading in the South China Sea. In addition to the Proto South China Sea history, the subduction of the Izanagi plate and the Izanagi-Pacific mid-oceanic ridge in the Eocene had significant geodynamic consequences for the East Asian margin. Our models allow us to track the source and trajectory of slabs in the mantle, which provides some first-order insights on the evolving interaction between mantle and surface processes (e.g., dynamic topography, sea level, etc.). The results have implications for paleobiogeography, basin evolution, oceanic circulation, mineral and hydrocarbon resources, as well as helping us better understand the structure and evolution of the mantle in this tectonically complex region.

Relevant papers:

1. Zahirovic, S., Seton, M., and Müller, R., 2014, The Cretaceous and Cenozoic tectonic evolution of Southeast Asia: Solid Earth (EGU), v. 5, p. 227-273.
2. Zahirovic, S., Flament, N., Müller, R. D., Seton, M., and Gurnis, M., 2016, Large fluctuations of shallow seas in low-lying Southeast Asia driven by mantle flow: Geochem. Geophys. Geosys, v. *Frontiers in Geosystems: Deep Earth - surface interactions*, no. 17.
3. Zahirovic, S., Matthews, K. J., Flament, N., Müller, R. D., Hill, K. C., Seton, M., and Gurnis, M., 2016, Tectonic evolution and deep mantle structure of the eastern Tethys since the latest Jurassic:

Earth Science Reviews, v. 162, p. 293-337.

Mantle convective heat flux to continental lithosphere

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It has been well established that surface heat flux on continents has two main sources of contribution: 1) radiogenic heating from radioactive delays of ^{238}U, ^{232}Th, ^{235}U and ^{40}K in the continental crust that is enriched with these radioactive isotopes, and 2) mantle convective heat flux through the base of the lithosphere. The relative importance of crustal radiogenic heating and mantle convective heat varies among different continental regions. For example, in Canadian shields, the surface heat flux and its variability are largely controlled by radiogenic heating in the crust, but in the western United States, mantle convective heat flux plays a dominant role. This presentation is mainly on causes and effects of convective heat flux. Convective heat flux beneath the lithosphere is derived from gravitational instability of the top thermal boundary layer of the convective mantle for which the lithosphere is part of. The lithosphere with its relatively small temperature (i.e., cold) and negative buoyancy is gravitationally unstable. However, with temperature-dependent viscosity, only the bottom portion of the lithosphere (i.e., the sub-layer) with its relatively high temperature and hence small viscosity may go unstable. When the instability happens, the sub-layer becomes part of sub-lithospheric small-scale convection system. The small-scale convection associated with the sub-layer controls the convective heat flux supplied from the mantle to the lithosphere. The sub-layer has a differential temperature of an order of 100 K that however depends on activation energy of diffusion and dislocation creep deformation. The sub-layer thickness is controlled by convective Rayleigh number of the mantle. The differential temperature across and thickness of the sub-layer determines the convective heat flux into the lithosphere. This convective heat flux, together with radiogenic heating in the crust, controls the lithospheric thickness. The sub-lithospheric small-scale convection process is rather general and most likely operates in the South China region.

Magmatism and related subduction processes in coastal region of South China

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Petrology, rock fabric, U-Pb and Hf-Sr-Nd-Pb isotopes, whole rock geochemical data are used to constrain the evolution of Mesozoic high potassium granitic rocks that record an Andean type orogenic cycle in the southeastern China segment of the Western Pacific. Decreasing melting pressures of the granitic magmas from the Late Triassic to the Early Cretaceous, as reflected by decreasing Sm/Yb ratios, point to a general trend of crustal attenuation with time in western Zhejiang Province. Five distinct stages of granitic magmatism are identified: (1) 230-215 Ma: high-temperature, high-pressure dehydration melting in a reduced and thickened crust caused by flat-slab subduction of the paleo-Pacific Plate; (2) 170-150 Ma: low-temperature, high-pressure water-fluxed melting in an oxidized and thickened crust caused by the foundering of the paleo-Pacific Plate; (3) 140-130 Ma: low-temperature, low-pressure dehydration melting of the continental crust caused by extension of the lithosphere; (4) 130-125 Ma: high-temperature, low-pressure dehydration melting of the refractory materials in the continental crust caused by further extension of the lithosphere and possibly basaltic underplating; and (5) 115-100 Ma: emplacement of differentiation products of hydrous basalts from the mantle enriched by subduction. The formation of 115-100 Ma granitoids reflect strong mantle-crust interaction and growth of new continental crust; the mafic microgranular enclaves (MMEs) in these rocks mostly have coaxial fabrics with host granitoids and likely represent mafic magma flowing with granitic magma.

3 Method for predicting a geoneutrino signal at a detector

Geological models seek to accurately and precisely describe the flux of geoneutrinos at a detector. Here is brief description of the standard template for achieving this goal. It is a holistic geological approach. Overall, the strategy involves gathering and integrating as much geology, geophysics and geochemistry of an area close to the detector (generally the first 500 km) and incorporating it into a 3D physical and chemical description of the lithosphere. The signal is typically treated as having 3 components (1) local lithosphere, (2) far field lithosphere, and (3) mantle, with an assumed negligible contribution from the Earth's core. The detected signal scales directly with the abundance and distribution of Th and U (the only detectable contributors to the signal), given detector sensitivity scales as $1/R^2$, with $R = r - r'$ being the separation distance between detector (r) and source (r').

There have been a series of published models that have predicted the flux of geoneutrinos at the following detectors:

- KamLAND: *Enomoto et al.* (2007)
- Borexino: *Coltorti et al.* (2011)
- SNO+: *Huang et al.* (2014)
- JUNO: *Strati et al.* (2015)
- Jinping: *Šrámek et al.* (2016)

The overall 3D model follows a standard layout (see, e.g., *Huang et al.*, 2013, for details), a lithosphere overlying a mantle, with a lithospheric structure following that set up used in CRUST 2.0 and its successors (i.e., CRUST1.0 and LITHO1.0). The lithosphere has 8 layers:

1. water
2. ice
3. soft sediment
4. hard sediment
5. upper crust
6. middle crust
7. lower crust
8. lithospheric mantle

Beneath this lithosphere is a mantle that is generally treated as an isotropic shell or is divided into two vertically separated domains of contrasting abundances of Th and U (e.g., a thick Depleted Mantle overlying a thinner Enriched Mantle). The underlying metallic core is treated as not contributing to the signal.

Globally, most models have an areal resolution is $1° \times 1°$, by 8 layers. For these studies the Earth is divided into two regions (1) a near field crust (NFC or local crust) and (2) a far field crust (FFC). As first pointed out by *Araki et al.* (2005), the closest 500 km to the detector contributes approximately 50% of the signal and so this is the working definition of the NFC. The FFC uses the global resolution scale, while the NFC has a finer scale resolution.

Efforts on JUNO will follow the practices used in previous studies (see, e.g., *Huang et al.*, 2014; *Strati et al.*, 2015; *Šrámek et al.*, 2016, for details). In the SNO+ study of *Huang et al.* (2014), the NFC surrounding the detector was divided into a 440 km × 460 km × 42 km deep area. Each tile described in this region was assigned a V_p, V_s, density value and a SiO_2, K, Th, and U content.

Seven dominant surface geological units were identified in *Huang et al.* (2014) to describe the upper crust in the SNO+ 3D model. A simplified version of the surface geology was combined with information for the vertical crustal structure obtained from refraction and reflection seismic surveys. Depths to the top and bottom of the middle crust and to the MOHO (bottom of the lower crust) were defined seismically, based on contrasts in V_p and V_s. Uncertainties associated with the average depths of the middle and lower crust were treated as correlated and their sum corresponds to an average uncertainty. Densities of the middle and lower crust were estimated using the relationship reported in *Christensen and Mooney* (1995) for V_p and density.

In the SNO+ study abundances of U and Th in the upper crustal lithologies were based on analyses of representative outcrop samples and literature data. Abundances of U and Th in middle and lower crustal lithologies were treated in the same manner as in Huang et al (2013), which was based on a global database for appropriate pressure and temperature rocks (i.e., granulites and amphibolites). Uncertainties associated these data were assessed and correlated errors for Th, U, and K were treated. Correlations between V_p and SiO_2, as defined in *Huang et al.* (2013), were used to assign chemical attributes (mafic to felsic proportion) to physically defined crustal tiles.

At SNO+, to predict the geoneutrino signal and assign precise oscillation parameter values, the 3D regional crustal model was divided into cells of 1 km × 1 km × 0.1 km dimension, generating a grid having 9×10^8 cells. In each cell spatial, geophysical, and geochemical data were assigned.

For JUNO, a research group has already conducted an extensive campaign of geological sampling and chemical analyses, as well as literature searches. Xi Yufei and her colleagues have gathered samples from some 300 localities close to the JUNO site. Her sampling campaign targeted critical geological units and was designed to assess the chemical variability in these local lithologies. Following this, efforts will be invested into treatment of uncertainties in these units and integrating these findings with further studies.

In addition to direct field sampling of local geological units, a concerted effort is required to identify and critically review the available geological, geochemical and geophysical data for the immediate area surrounding the JUNO site and beyond. A dedicated task of integrating relevant studies will be needed and these studies include: a) seismological studies, including reflection and refraction profiles, ambient noise, surface wave, and body wave tomographic studies, and receiver functions, b) heat flow studies, c) gravity studies, and d) geochemical compilation. As these data accumulate they will be incorporated into a 3D physical and chemical model.

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