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Antarctic melting: Natural or Anthropogenic?

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Abstract: The melting process and mechanism of the Antarctic ice sheet and its influence on the global sea level change are the major issues of global concern, and also the hot topic of the recent year dispute. The global warming theory elegantly accounts for sea level rise due to the CO_2 greenhouse effect as a consequence of human activities, by accelerating the deglaciation in Antarctica. However, observations show that subglacial water such as the Lake Vostok beneath Antarctic ice sheet as a consequence of basal melting is an important source of water contributing to the rise in sea levels. Besides, basal melting will reduce the buttressing of ice shelves, which may lead to glacier thinning, its acceleration and grounding line retreat. Here, we considered that the high heat flux of the rock under the ice cover may provide an explanation of global sea level rise by leading to the ice melting under the thermal heated ice sheet. We think that the volcanic action, the high heat flow rifting effect and other geothermal resources are most of the important causes of the basal ice melting. These recent findings of ice melting beneath Antarctica highlight the need for better understanding subglacial geothermal sources, their hydrologic interactions with marine margins, and their possible roles in global climate change.

Keywords: Antarctic ice melting, rifting, heat flow, sea level

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Антарктическое таяние: природный или антропогенный процесс?

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Резюме: Процесс и механизм таяния антарктического ледового щита и его влияние на глобальное изменение уровня моря являются основными проблемами, вызывающими общемировую обеспокоенность и горячие споры в течение последних лет. Теория глобального потепления элегантно объясняет повышение уровня моря из-за парникового эффекта CO_2 как следствие человеческой деятельности, ускоряющей дегляциацию Антарктики. Однако наблюдения показывают, что подледниковая вода, такая как озеро Восток под антарктическим ледяным покровом, возникшая вследствие таяния грунта, является важным источником воды, способствующим повышению уровня моря. Кроме того, подледниковое таяние способно уменьшить опору ледяных шельфов, что может привести к истончению ледника, его сокращению и отступлению от существующей линии границы. Мы посчитали, что высокий тепловой поток в горных породах под ледниковым щитом приводит к его термическому нагреву и таянию и тем самым может объяснить глобальное повышение уровня моря. Мы считаем, что наиболее важными причинами таяния базального льда являются вулканические воздействия вследствие эффекта рифтинга, высокий тепловой поток и другие геотермальные ресурсы. Эти недавние находки таяния льда под Антарктидой подчеркивают необходимость более глубокого понимания подледниковых геотермальных источников, их гидрологического взаимодействия с морскими окраинами и возможной роли в глобальном изменении климата.

Ключевые слова: таяние антарктического льда, рифтинг, тепловой поток, уровень моря

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The stability of the Antarctic ice sheet is of paramount importance to global sea level rise. However, climatic models describing responses of ice-sheet to global change are still not complete [1]. The global warming theory elegantly accounts for sea level rise due to melting ice in Antarctica, which is thought to be caused by the CO_2 greenhouse effect as a consequence of human activities [2]. It is believed that human activities deliver large amounts of CO_2 to the atmosphere, inducing the greenhouse effect, accelerating the deglaciation in Antarctica, and resulting in a big rise in sea level as a consequence of melting ice [2, 3]. However, this explanation does not appear to explain areas of unusually profuse subglacial melting underneath huge ice sheets on the continental lithosphere [4–12].

Subglacial water beneath Antarctic ice sheets as a consequence of basal melting is an important source of water contributing to the rise in sea levels. Besides, basal melting will reduce the buttressing of ice shelves, which may lead to glacier thinning, its acceleration and grounding line retreat, and melting land-ice cover may reduce load from the crust to activate elastic rebound [13]. Satellite data already revealed that no less than 200 buried lakes beneath Antarctica's continental ice sheet exist [9]; among them is the world's seventh largest lake, i.e., Lake Vostok (Fig. 1-A) located at the center of the East Antarctic Ice Sheet (Fig. 1) at approximately one kilometer deep with fourteen thousand square kilometers in area (Fig. 1).

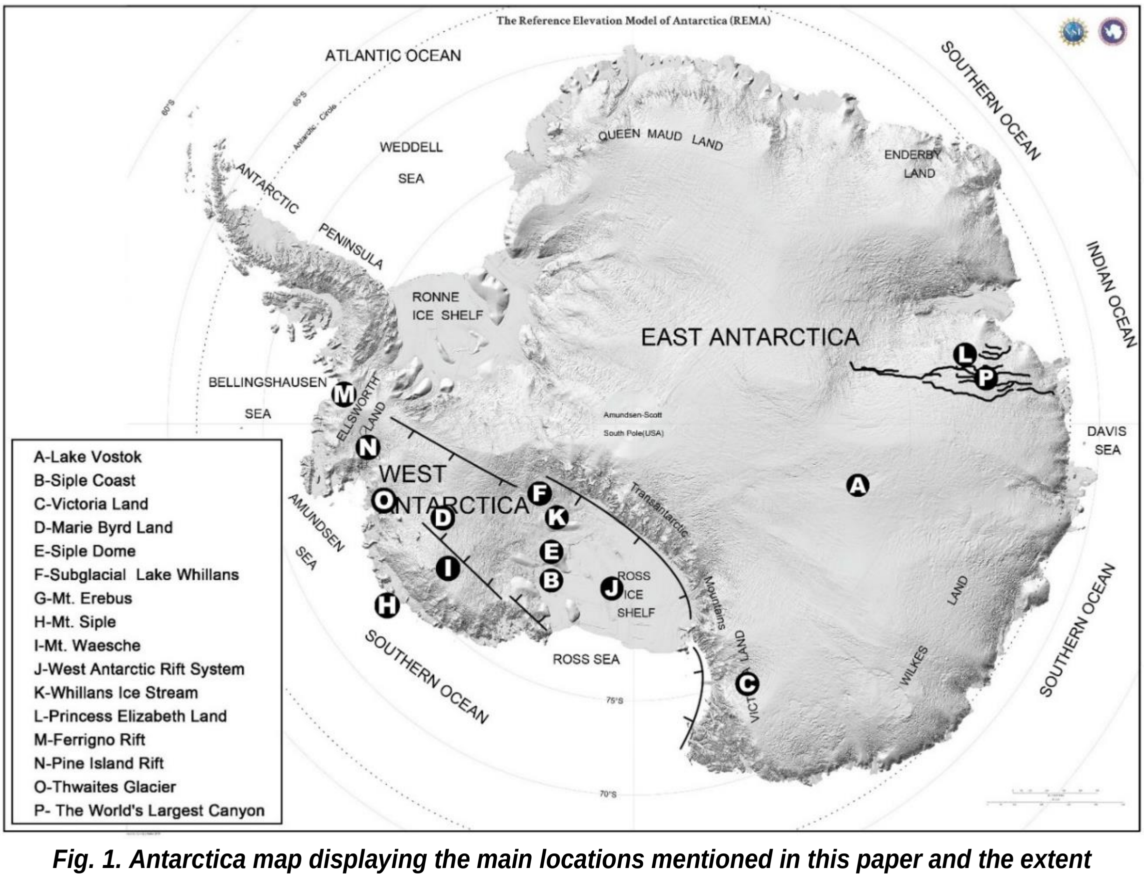

Fig. 1. Antarctica map displaying the main locations mentioned in this paper and the extent of the West Antarctic Rift System (redraw from Howat et al. [14])

Рис. 1. Карта Антарктики, показывающая основные места, упомянутые в статье, и Западно-Антарктическую рифтовую систему (взято из Howat et al. [14])

Because its bed is grounded well to the continent, the subglacial melting underneath the Antarctic ice sheet may depend on geological controlled conditions at the base which are independent of climate. During the past few decades, researchers have recognized the solid Earth as a thermal system [15] and proposed an independent model of geothermal anomaly to account for this type of ice melting: high heat fluxes below subglacial rocks [10]. In recent years, China's scientists have made substantial progress in understanding Antarctic ice melting during their Antarctic exploration. Their 32nd expedition team detected large-scale "warm ice" under the sheet, along with a number of subglacial lakes [16]. Their onsite investigation suggests that geothermal anomalies are confined to the deep boundaries between ice and rock, which causes significant basal ice melting; they also found that many subglacial lakes and currents are interconnected, forming a giant "wetland" beneath the Antarctic ice. They recognized that such melting is more compatible with a deep, warm and distributed source controlled by the lithosphere, than with a surface effect controlled by climate warming.

Recently, more observations demonstrate that strong regional changes of the geothermal flux greatly influence the geothermal regime and the ice-base melting beneath the continental parts of its ice sheets [5, 11]. And as a results, large parts of its ice sheet are currently melting from below. Maule et al. [8] also found elevated heat fluxes both around Siple Coast and along the East-West Antarctica boundary (Fig. 1-B), and heat fluxes of similar high value were recorded around Victoria Land (Fig. 1-C) and near the shores of West Antarctica. At Siple Coast (Fig. 1-B), where elevated heat fluxes were found, several ice streams exist, and it was previously argued that heat from the ice sheet base might be one of the major trigger mechanisms for the formation of these fluxes [4–8]. The analysis of Rayleigh wave paths that cross Antarctica reveals low-velocity structures have been interpreted to support the Marie Byrd Land (Fig. 1-D) hotspot hypothesis [17]. Energy balance models [18] prove that underneath one of the Siple Coast ice streams (Fig. 1-B), heat flux must be higher than 80 mW/m^2 to keep ice-base melting, which is the same as they found for this area. The monitoring value at Siple Dome (Fig. 1-E) was 69 mW/m^2 according to Engelhardt [7]. Fisher et al. [12] reported the geothermal heat flux measured directly for the first time from the ice base of the West Antarctic Ice Sheet (WAIS), below Subglacial Lake Whillans (Fig. 1-F), and determined this according to the geothermal gradient as well as the geothermal conductivity of sediments under the subglacial lake. At this site, a surprisingly high heat flux, 285 ± 80 mW/m^2, was found, which is greatly higher than the continental and regional average values. They also found that the upward heat flux of 105 ± 13 mW/m^2 at the WAIS has been indicated by independent temperature measurements in the ice. The obvious difference between the heat fluxes might contribute to ice-base melting and/or be transferred from Subglacial Lake Whillans (Fig. 1-F) to other places through flowing water. Also, the formation of very abundant and dynamic ice streams and subglacial lakes could be explained by considering the high geothermal heat flux [12].

Although determining whether natural geothermal sources or anthropogenic CO_2 effects cause ocean warming is complicated and very controversial, these matters become simpler for the continental lithosphere beneath the ice capes. It is well-known that the interior of the Earth is much hotter than the surface. The heat is partially leftover from the early Earth, however it is continuously produced by the radioactive element decay and the inner core crystallization [1, 19]. These are both important sources of heat to the flux released from the mantle. Where there is ice, the ice sheets function as a lid so that more heat is accumulated beneath the ice sheet. Therefore, in evaluating Antarctic ice melting, geothermal fluxes should be one of the most dynamically critical boundary conditions of ice sheets. Present global warming hypothesis seems to not account for these unexpected observations of the Antarctic basal ice melting as a consequence of geothermal heat flux anomalies.

In the longer term, Earth evolves as a thermal system. Our recent studies for Earth's thermal evolution, as shown in Fig. 2, suggest that Earth may experience extremely warming and cooling periods in terms of changes in the heat balance of the Earth system [15]. In the shorter term, however, the expansion of the lithosphere and its associated uplift may lead to rifts or fractures in Earth's crust, with volcanism and magmatism as the consequences. These may allow shortly a large quantity of heat release into the surface. Therefore, the supply of thermal energy makes basal ice melting, water production and reduction of basal friction unavoidable.

It is not difficult to understand these geothermal sources as a cause of the basal ice melting. The argument against this geothermal influence may be due to their time scales. It is generally believed that the effects of heating glaciers from below is a long-term issue rather than a short-term one, since the geothermal heat flux through the surface is generally considered to be a constant [1]. But thick ice sheets are sensitive to both temperature fluctuations from above and short-term geothermal heating from below, in terms of tectonic events, which often take place in catastrophic ways. Unfortunately, in ice sheet dynamics, most existing models focus on the way they interact with climate system, only taking into account simplified representations of the solid Earth, for instance, by considering basal heat flux as a constant boundary condition or by modeling the lithosphere using a simple elastic plate [1]. Thus, the current models may fail to replicate in-site basal ice melting and temperature measurements of ice base in Antarctica.

Subglacial volcanism underneath the Antarctic ice sheet is recognized as one of the most important mechanisms related to possible short-term geothermal disturbances to basal ice melting. Maule et al. [8] found that areas of high heat flux are in accordance with currently known volcanism and several areas owning ice streams. Up to now, at least 138 volcanoes have been determined across West Antarctica [20], including the presently active volcano named Mt. Erebus [21] (Fig. 1-G) along the Terror Rift, as well as Mt. Siple [21] (Fig. 1-H) and Mt. Waesche [22] (Fig. 1-I), which both of them display evidence for recent activities [23]. Tectonic landforms reveal that the WAIS covers a huge volcanic rift system. The distribution of mantle helium in glacial melting water indicates that it is volcanic heat that leads to melting beneath the grounded glacier and contributes to the

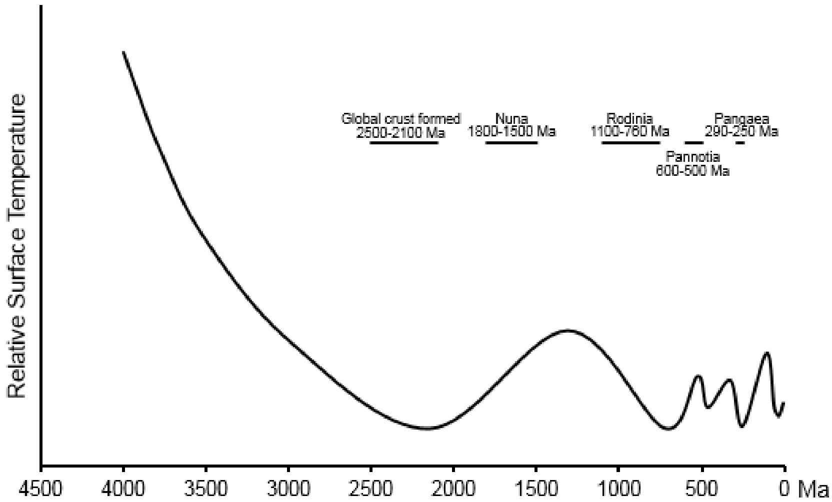

Fig. 2. Earth evolution as a thermal system
(relative surface temperature fluctuation, redraw from Tang and Li [15])
Рис. 2. Эволюция Земли как тепловой системы
(относительные колебания температуры поверхности, Tang and Li [15])

subglacial hydrological system crossing the grounding line. Also, the visible surface deformations in the thickness of the WAIS demonstrate localized heat fluxes which are possibly volcanic, because of the intensity ([4, 21], while more recent eruptions are revealed by the ash layers from ice cores [24]. Several fast-flowing ice streams draining the WAIS's interior regulate the mass balance of the WAIS [25]. The presence of active volcanism beneath the WAIS would be able to trigger its collapse because of enhanced ice base melting [4], leading to as high as 6 m of sea-level rise [26]. The production of free water because of basal melting, a value highly depending on geothermal heat fluxes, is critical to the ice streams in terms of their initiation and maintenance [27]).

Continental rifting, canyons or faults are other alternatives to the volcano. Geothermal forces will often cause crust expansion, which may cause propagating rifts, deepening canyons or even faults in terms of earthquakes, to provide passageways for deep heat to the surface. Normally, the geothermal flux is both higher and more variable for a rift system containing blocks of crust or sediments of varying thickness [7]. Although it is still unknown about the crustal structure, because of the vast size of the ice sheet, the West Antarctic Rift System (Fig.1-J) is believed to be one of the largest zones of abundant continental geothermal activities by connecting the land surface with the canyon bottom [28]. The widespread anomalous mantle heat flux in the active lake system of the lower part of the Whillans Ice Stream (Fig.1-K) is suggested to be linked to a rift source [29]. Jamieson et al. [30] found evidence showing that a previously undiscovered, large subglacial drainage network system is now hidden beneath the ice sheet in Princess Elizabeth Land (PEL) (Fig.1-L), which is believed to be tectonically linked to many long and deep canyons. Bingham et al. [31] hypothesize that the Neogene reactivation also occurred in the Ferrigno Rift (Fig.1-M) and Pine Island Rift (Fig.1-N) regions, potentially causing enhanced geothermal heat fluxes that would increase the availability of meltwater at the base of the WAIS. Recently, by combining radar sounding and subglacial water routing, Schroeder et al. [11] show that the Thwaites Glacier (Fig.1-O) may be one of the most significant, rapidly developing and potentially unstable contributors to global sea level rise in West Antarctica reflecting a geothermal flux consistent with rift-associated magma migration as well as volcanism. Schroeder et al. [11] showed that the minimum average geothermal flux value in the Thwaites Glacier catchment is 114 ± 10 mW/m^2, in addition to areas owning high fluxes that exceed 200 mW/m^2. Furthermore, their results indicate that the subglacial water network in Thwaites Glacier could be reflecting the heterogeneous and temporally variable ice-base melting induced by the development of the rift-associated volcanism and stand for the hypothesis that not only heterogeneous geothermal flux but also local magmatic processes might be dominant factors influencing the future behaviors of WAIS [11]. Again, China's 32nd Antarctic expedition team also contributed to this conclusion by confirming an earlier speculation that the South Pole is the site of the world's largest canyon (Fig.1-P).

In addition to providing connections between the ice and the deep underground for geothermal-enhanced basal ice melting, the 'rift-directed' offshore troughs will also form putative routes. Through these routes, warm open ocean waters can flow back and further penetrate the continental shelf to attack the ice margin [31].

The findings of geothermal ice melting seem to provide new evidence that contradicts the current mainstream concept of Antarctic ice melting in terms of CO_2 effects, which may be underestimated or even ignored by climate scientists. Instead of seeking an additional heat source, for example, that from climate change, the observed heat anomaly between the basal ice and the solid Earth is able to potentially give reason for the regional patterns of basal melting beneath the Antarctic ice sheet. Also, the same mechanism is valid for Greenland, in which geothermal heat fluxes from below are found to contribute to the conditions of basal ice melting underneath the ice caps, which sit atop a lithosphere of variable thickness (Fig. 3) [32]. Petrunin et al. [10] found that areas of rapid basal melting adjoins areas of extremely cold basal ice and the strong regional variations in ice-base conditions actually result from the complex interactions between geothermal heat flow and glaciation-induced thermal perturbations in the upper crust over glacial cycles. Their findings indicate that the structure of the solid Earth plays a certain role in the dynamics of surface processes.

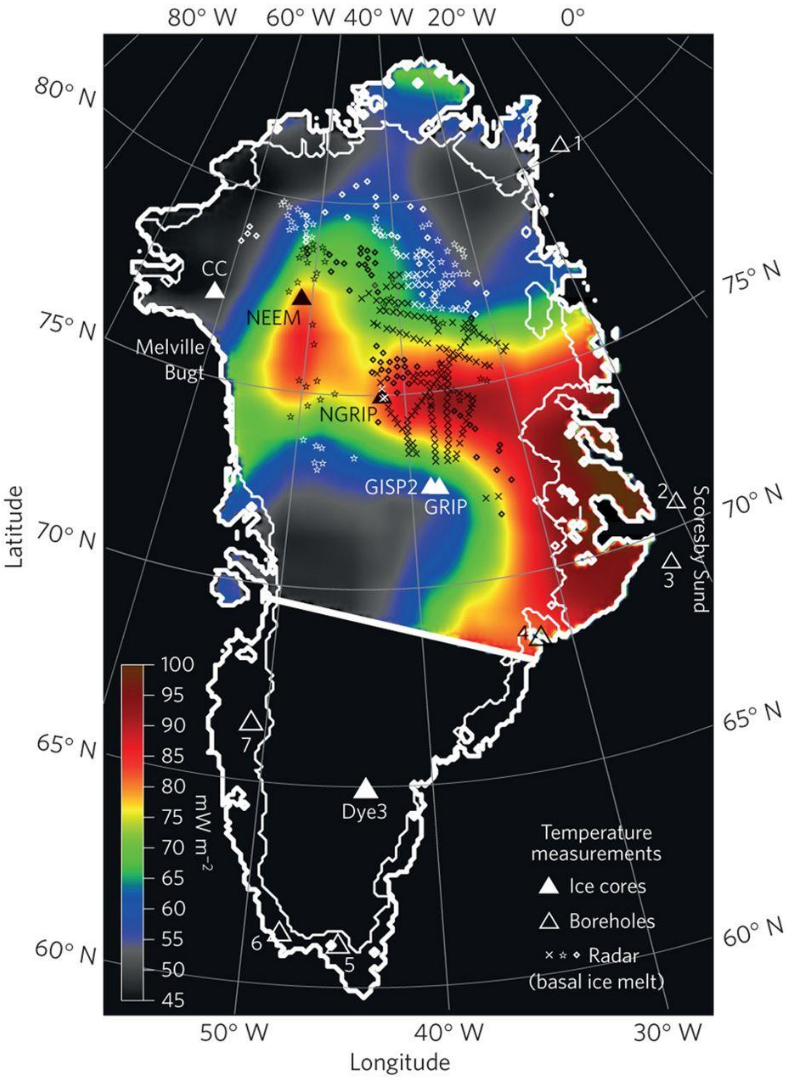

Fig. 3. Predicted geothermal flux (GF) at 5 km below the bedrock surface of Greenland (with permission from Dr. I. Rogozhina [32])

The GF was corrected for crustal heat production using a parameterization of radiogenic heat sources (see Methods in Rogozhina et al. [32]). The modelled thermal state of the GIS and lithosphere was calibrated by in situ data shown by white/black triangles, crosses, diamonds and stars (basal melting data are from radar and ice core measurements). The white curves outline the ice sheet and coastal margins

Рис. 3. Прогнозируемый геотермальный поток (GF) на глубине 5 км под поверхностью Гренландии (с разрешения доктора И. Рогожиной [32])

GF был скорректирован для подсчета геотермальных характеристик земной коры с помощью параметризации радиогенных источников тепла (см. «Методы» в Rogozhina et al. [32]). Смоделированное тепловое состояние ГИС и литосферы было откалибровано по локальным данным, которые показаны белыми / черными треугольниками, крестами, алмазами и звездами (данные по базальному плавлению взяты из измерений на радаре и в керне льда). Белые кривые очерчивают ледяной покров и береговые окраины

As a sub-product of deep melting effect, it was recognized recently that subglacial ecosystems support considerable methanogenic activities, thus significantly contributing the global methane production as a greenhouse gas [33, 34]. Melting conditions beneath about half of the ice sheet mean that sediments contain liquid water beneath the ice cover [8, 35]. The inferred methane hydrate reservoir beneath the Antarctic Ice Sheet is comparable to that in the Arctic region and could constitute a previously neglected component of the global methane hydrate inventory with a potential to act as a positive feedback on climate warming during ice-sheet wastage [36, 37]. Geological methane, produced largely via thermogenic processes in the deep subsurface, supplements the biogenic component [38]. It may be generated via the thermal breakdown of organic matter and by inorganic synthesis and outgassing from the mantle. The recent discovery that sub-ice-sheet environments are likely to be heated from below in terms of geothermal energy, may accelerate the production of methane. The findings from Ma et al. [33] highlight the effects of temperature and substrate on potential methanogenesis in the subglacial sediment of the Antarctia area, and may help us for a better estimation on its methane production in a changing environment. If substantial methane hydrate and gas were present beneath the WAIS, hydrate destabilization during episodes of ice-sheet collapse could act as a positive feedback on global climate change during past and future ice-sheet wastage [37].

This is an observation not a criticism on climate warming theory and simply reflects the essentially reconnaissance nature of most of the work to date on Antarctic thermal activities and our poor knowledge of the Antarctic lithosphere. All of these recent findings of ice melting beneath Antarctica highlight the need for better understanding subglacial geothermal sources, their hydrologic interactions with marine margins, and their possible roles in global climate change. Without considering the parameterization of the subglacial thermodynamics, hydrodynamics and ice dynamics, any model of climate change is incomplete. Before basal conditions can be correctly parameterized, ice-sheet models are not likely able to yield accurate results and evaluations of the impacts of global climate change on sea level rise in terms of ice melting, and analyses will keep flawed. As Kaus [1] reminds us in his comment on the work of Petrunin et al. [10]: “The solid Earth is not a force that can be ignored – it is an active player in surface processes. As we focus our attentions in a warming world on the atmosphere, oceans and glaciers, we must not forget the planet itself knocking on the surface from below”.

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Доктор Тан, профессор кафедры (финансируется из программы Cheung Kong Scholar Министерства образования), является директором Центра глубинных подземных исследований (DURC) Даляньского технологического университета и ведущим профессором Китайского геологического университета (Ухань), Китай, вице-президентом Китайского общества механики горных пород и машиностроения CSRME, являлся председателем Китайской национальной группы Международного общества механиков горных пород. В 1984 году он начал писать свою докторскую диссертацию в Северо-Восточном университете, Шеньян, Китай, где и получил докторскую степень в 1988 году. В 1991 году он продолжил свою докторскую работу в Имперском колледже, Лондон, Великобритания. Затем в качестве гостя-академика он получил большой опыт работы в Канаде, Швеции, Сингапуре, Швейцарии и Гонконге. Он возглавляет несколько крупных исследовательских проектов в области механики горных пород, особенно в области анализа и мониторинга процессов разрушения горных пород в строительстве, и является главным научным сотрудником Национальной программы фундаментальных исследований 973. На сегодняшний день он опубликовал более 300 технических статей о механизмах разрушения горных пород и строительстве, а также является автором пяти китайских книг по механике горных пород и основным автором книги «Механизм разрушения горных пород», опубликованной CRC (Taylor & Francis Group, 2010 г., Великобритания).