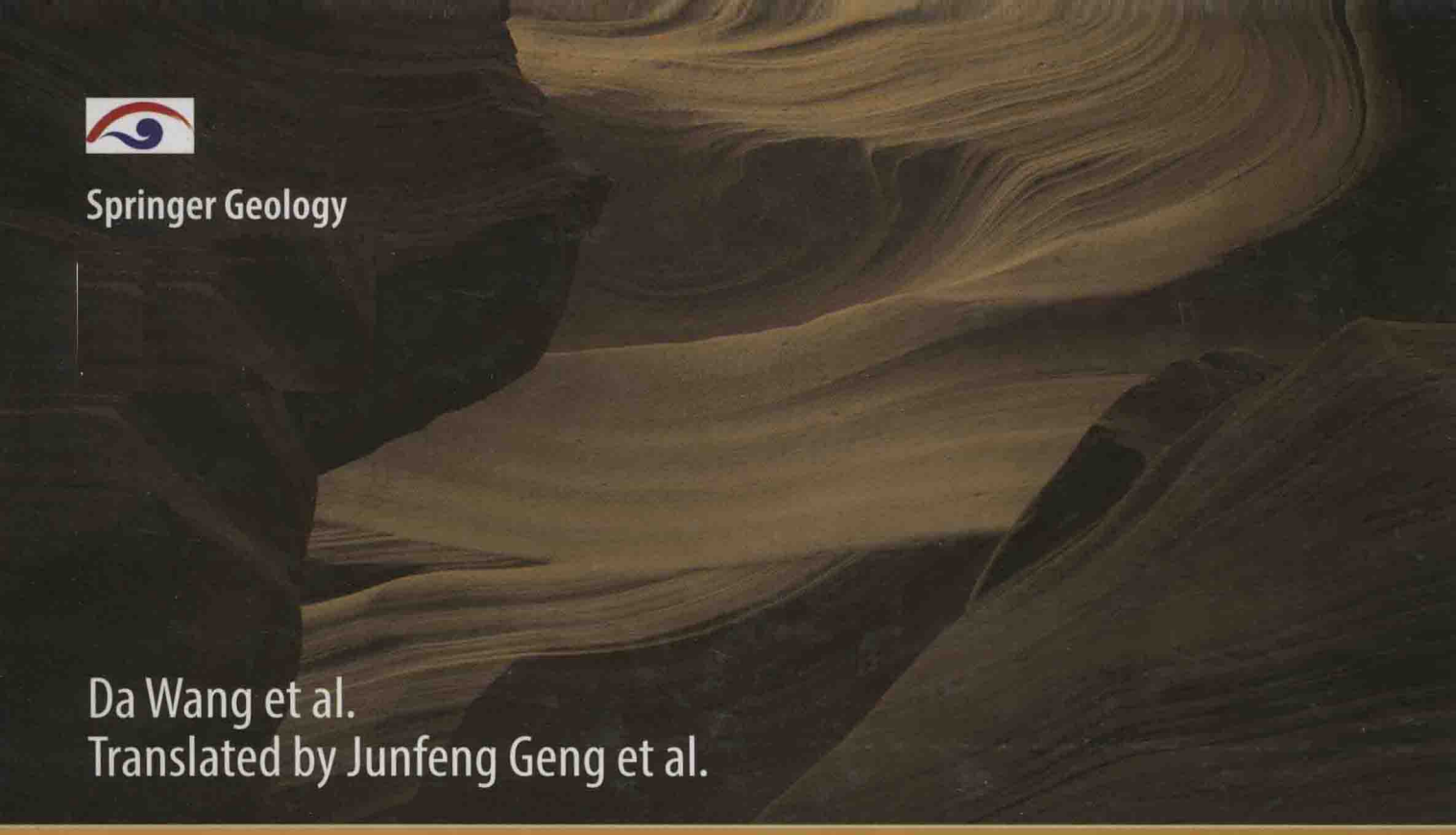

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Foreword I

Jules Verne, the originator of science fiction in the world, wrote a science fiction, Journey to the Center of the Earth, in which he tried all his imaginations to describe various scenes of the Earth's core. The Earth carries billions of human beings and life, and what does her core really look like? Freezing ice storage, or a hot lava chamber? So far, a great variety of speculations about the Earth have been bringing to scientists all kinds of interesting mysteries for a long time.

After World War II, the world experienced a period of relative stability, and geologists got opportunities to make long-term continuous research on the deep Earth. They conceived to use modern ultra-deep drilling techniques, to drill into the deep Earth, obtain the cores, and analyze the various characteristics of rocks; to place the geophysical and geochemical and many other modern scientific instruments into borehole to get the data of borehole profile; to study the evolution of the Earth's crust by using the cores and surveyed data; and to convert geology from relying mainly on inference to relying mainly on verification through survey, which could be called "the digital Earth"; and the traditional geology could be converted into "the Earth Science" by the increased understanding of the deep Earth, which would be a great leap forward.

The rise of scientific drilling should be in the middle of the twentieth century. NEDRA, an institution of ultra-deep drilling consortium, led by the minister in the Ministry of Geology in the former Soviet Union, successively implemented many scientific deep boreholes. B.N. Khakhaev, the General Manager, specifically presided at the engineering design and construction works. During the construction process, they carried forward the great Soviet tradition of "no saying, just doing" and eventually announced the success of the world's first ultra-deep drilling when drilled to the depth of 12,262 m in SG-3 Well in Kola Peninsula. The news immediately spread around the world, startled the world drilling circles, and dedicated a great amount of the latest Earth information for the Earth Science research as well, for example: 1. The upper and lower boundaries of the local upper mantle and lithosphere, and their respective thicknesses were preliminarily clarified; 2. the fluid which "shouldn't appear" (from E.A. Kazlovski, the former minister in the Ministry of Geology in the former Soviet Union) and the abiogenetic oil and gas were astonishingly found, by which the inference of a young man from the United States in the 1940s was confirmed; and 3. lots of the latest and the most authoritative geological information data were obtained.

Thus in 1988, in the former Soviet Union was held an international scientific drilling conference, at which most of the non-confidential information and achievements were released. The finding of abiogenetic oil and gas immediately attracted a delegation from Sweden, a country lacking in oil and gas. The delegation returned even before the meeting was closed, and designed and constructed two deep boreholes—Gravberg 1 and Gravberg 2. The achievements of the scientific drilling in the former Soviet Union were huge, greatly shocked the geology circle in the world, and promoted a continuous flourish and climax of scientific drilling.

A part of scientific drilling was started from the ocean, because a great quantity of solid strata have to be drilled at the beginning of land drilling, for instance: 1. In 1968, Deep Sea Drilling Project (DSDP) was executed by Glomar Challenger drilling ship; 2. in 1985, the Ocean Drilling Program (ODP) was started, with JOIDES Resolution as the academic leadership. At the 184th voyage, a borehole was drilled in the South China Sea. The program has made a series of great scientific achievements; 3. in 2003, Japan Marine Science and Technology Center (JAMSTEC) and the existing ODP members combined into the new Integrated Ocean Drilling Program (IODP).

Our country has a long history of geology. Geologists of the older generation successively put forward their suggestions and ideas to conduct scientific drilling projects a number of years ago. For instance, Li Siguang in 1950, Zhang Wenyou in 1959, Xie Jiarong in 1965, and Li Chunyu and the famous geophysical expert Gu Gongxu in 1988 successively put forward the same idea that scientific drilling was the only way to obtain geological materials from deep Earth for further development of geology in our country.

Comrade Deng Xiaoping proposed the brilliant thesis "Since the Chinese people were able to stand up, they will surely be able to stand firm forever among the nations of the world," which greatly inspired the exploration engineering workers. In September 1979, the first exploration engineering conference was held in Beidaihe; in the conference was put forward a proposal of making preparation for the first scientific borehole in the People's Republic of China, which won wide support from the exploration engineering circle. Many famous geologists, such as Jia Fuhai, Chen Mengxiong, Zhao Wenjin, Li Tingdong, Xiao Xuchang, and Xu Zhiqin gave strong support to this proposal. Hereafter, the scientific drilling project in China experienced the procedures of project argumentation and demonstration, examination, approval and site selection, and the National Laboratory of Scientific Drilling was established.

In 1992, the Ministry of Geology and Mineral Resources hosted the first seminar on China Continental Scientific Drilling. In February 1996, China officially joined ICDP. In September 1997, the China Continental Scientific Drilling Project was listed as a national major science project in the ninth Five-Year Plan period (1996–2000).

On June 25, 2001, CCSD-1 Well, the first hole of the China Continental Scientific Drilling (CCSD) Project, was opened. Taking only 1,353 days, CCSD-1 Well was drilled to 5,158-m-deep and 4,290.91-m core was recovered, with an average core recovery of 85.7 % and an average penetration rate up to 1.01 m/h. In the whole construction, the equipment and tools with totally independent intellectual property rights of China were employed, and a variety of geophysical measurements were undertaken during the drilling process. This is a tremendous contribution thanks to the close cooperation between the exploration field and many scientific research institutions of our country. The successful completion of CCSD-1 Well opened a new page for the study of Earth Science in China, and is a great and important step forward transforming from a big geoscience country into a powerful one.

The practice of CCSD-1 Well proved that only by scientific innovation, the world top-class achievement could be obtained. The constructors creatively combined the "combined drilling technology," the "flexible double-hole program," and the "feel-ahead with small diameter core drilling method" organically, and formed a complete set of unique scientific drilling technology systems with Chinese characteristics. And particularly, they successfully developed the downhole power drive (PDM + hydro-hammer) percussive rotary diamond core drilling technique system as the world origination. China Continental Scientific Drilling Project is a successful model of scientific innovation in our country.

This book, a monograph, incorporates theory, experience, and application and is a crystallization of the wisdom of three generations of drilling technicians. The publication of the book induces much thinking and enlightenment, and will surely play a great role in the continuous development and improvement of the drilling techniques in our country.

Science is endless and so is continental scientific drilling. This book will undoubtedly inspire us to continue climbing to new heights with new actions and make greater contributions to the continuous development of scientific drilling, with the success of CCSD-1 Well as a new starting point.

Beijing, October 7, 2014

Liu Guangzhi
Academician of the Chinese Academy of Engineering

Foreword II

After years of preparation, China Continental Scientific Drilling (CCSD) Project was officially selected as a major national science project in the ninth Five-Year Plan period. And after nearly four years of serious construction, the first scientific well of our country (CCSD-1 Well) was successfully completed with outstanding results, for which I feel very happy and gratified.

The successful completion of CCSD-1 Well is a memorable event in China's exploration engineering industry, which changed the previous situations of "paper drilling" or "oral drilling" (not to despise the theoretical knowledge or book knowledge, but refer to the empty talk), and this qualitative change was not easy. Now, we have really drilled a scientific drilling hole for more than five thousand meters deep, which has been implemented in Donghai, Jiangsu Province in China. This fact is very valuable. Genuine knowledge comes from practice, which is the basis of understanding objective things, and is the sole criterion for testing truth as well. Whether our various understandings toward drilling engineering are correct or not can only be judged by practice. I think we can now participate in international scientific drilling seminars with well-regulated minds and with self-confidence. This does not mean we are arrogant, but we feel sure of the genuine facts. That is the value of practice.

CCSD-1 Well is a continental scientific drilling project with Chinese characteristics. According to the goal of continental scientific drilling and in light of the requirements for full borehole coring in hard rocks in deep crust, advantages and advanced techniques of geological drilling and oil drilling were fully applied, and new improvements and innovations were made on the basis of the two technologies, so as to get excellent achievements. During the construction, there were many presentations with Chinese characteristics, which are introduced in detail in the book, and can also be found by drawing comparisons with foreign scientific drilling constructions.

CCSD-1 Well is a world-class continental scientific drilling project, which has experienced a course of having a high regard for science and boldly overcoming miscellaneous difficulties, and has left a brilliant page for the development of drilling techniques in our country. It was a tricky problem while coring (sampling) in hard rocks in deep well. To overcome this, the technique of PDM and hydro-hammer drive swivel-type double-tube impregnated diamond core drilling was originally created. This new downhole drilling tool assembly greatly improved the dynamic condition of bottomhole, stabilized the conditions of drilling tool rotation and vertical feeding, increased penetration rate and core recovery, improved straightening effect, and has become an advanced downhole drilling tool assembly for coring and straightening in deep hard rock drilling. In fact, we can fully understand the working conditions of the drilling tool at hole bottom based on the core obtained, which is not only a basis for evaluation of geological work, but also the basis for identifying downhole drilling conditions. During CCSD-1 Well drilling construction, a piece of core more than 4 m was recovered; the well-distributed scratches were the best evidence of the bottomhole drilling conditions.

The rock layers drilled in the continental scientific drilling project were hard and dense. The hole wall protection mechanism is different from that of oil drilling, in which sedimentary strata with formation pressure are to be drilled. In CCSD-1 Well, drilling fluid, the flowability

and lubricity of which greatly influenced drilling process, also played the role of a medium transmitting downhole power. In view of such peculiar conditions and requirements, a special drilling fluid was successfully developed, which effectively reduced frictional resistance and wear of the drilling tool and also significantly reduced the circulation resistance in small annular clearance in deep hole, ensuring normal and efficient drilling. As a matter of fact, the drilling fluid system for the hole is a model with Chinese characteristics fully adapting to the needs of scientific drilling, and since then, the previous situation of totally contracting out the drilling fluid to oil drilling mud companies has been changed.

The implementation of scientific drilling is an advanced system engineering project, whole chains of which are mutually supported and restricted, working in synchronization. The concepts and measures worth mentioning are widespread, of which this book has given detailed explanations. I think the following points should be mentioned:

Flexible Double-Hole Program

The double-hole program, which is divided into the pilot hole and the main hole, was an initiative of the KTB project in Germany and was based on their own objective conditions. While waiting for the newly developed deep well drill rig, they used the ordinary oil drill rig to drill a pilot hole to race against time, avoiding any delay in drilling the pilot hole and the main hole. A double-hole program was also adopted in CCSD-1 Well; however, whether to move the hole position was to be decided according to the actual results of the pilot hole drilling. This decision was not only stochastically flexible, but also at a higher level in decision making, in comparison with the decision of moving hole position before drilling. Drilling practice showed that this strategic concept promoted the requirements for pilot hole construction that vertical drilling should be guaranteed for better coring. As a result, after the completion of 2,000-m-deep pilot hole, the deviation angle of the hole was only a little more than four degrees, and the main hole could be continued right in the pilot hole. Then one-hole program was realized after hole expanding. It was proved that the flexible double-hole program had saved large funds.

Selection of the Drill Rig

The new advanced ZJ70D oil drill rig was selected for drilling CCSD-1 Well. This laid a good foundation. However, the drill was mainly designed and made for oil drilling (cone bit, high weight on bit, and low rotary speed). In order to meet the requirements in scientific drilling with impregnated diamond bits in hard rocks, some necessary modifications were made on the drill rig which was completely reasonable. The original brake system was modified, and an electronic driller system was installed to fully satisfy the requirements of smooth and accurate feeding for drilling with impregnated diamond drill bit, and a surface top drive or downhole PDM drive was applied to increase the rotary speed of the drilling tool so that the drilling speed of impregnated diamond drill bit could be guaranteed. Meanwhile, in order to ensure the cleanness and the stable properties of the drilling fluids, high-performance solid control equipment was specially selected and this equipment played a key role in high-efficient safety drilling. In addition, due to full-hole coring and long construction period of CCSD-1 Well, public electric power grid was applied instead of diesel generator power supply commonly used in oil drilling, and in this way, the power supply condition was improved. Practice indicated that the above-mentioned technical measures and decisions were wise, effective, and economical.

Measures and Understanding of Borehole Bending

People are always trying to drill boreholes straight, which is almost impossible and unnecessary because of various reasons. In drilling of the 2,000-m-deep pilot hole in CCSD-1 Well, borehole deviation was only 4.1 degrees, and this was an outstanding achievement of anti-deviation, which indicated that the formation cooperated and the anti-deviation technology was efficient. In the hole section of 3,500 m below, strong deviating strata were encountered, and a variety of anti-deviation measures adopted were not effective. It was understood through calculation that to the final well depth, the deviation and displacement of the well were both in the permitted range, and then it was decided to drill along the natural deviation tendency of the rock formations, and in this way, the risks of arbitrary deviation correction could be avoided, drilling rate was increased, and the expected goal was attained, with the advantages outweighing the disadvantages. This decision was reasonable and clever. In fact, the serious point of the well deviation is the sharp elbow (also called "dogleg"). Large dogleg degree can cause rotation difficulties of drill string and drilling tool and obstacles for running casing, directly affecting drilling operations.

Special Double Drive

As downhole PDM drive was adopted in CCSD-1 Well, the drill string of thousands of meters in the upper hole section was not in rotation. Practice indicated, however, that slight rotation of the drill string at the upper hole section is of benefit. Drill bit at hole bottom not only rotates, but also needs timely feeding, and slight rotation of the drill string at the upper hole section improves the feeding state, and smooth and stable feeding can be realized.

During the construction practice of CCSD-1 Well, much experience and new knowledge were obtained. The views above are just feelings of mine, which might not be definitely right but could be references for study.

This book is a comprehensive summary of the China Continental Scientific Drilling Project and a discussion of the implementation of CCSD-1 Well in all aspects. Different from the works of "book to book" (not to despise books, but refer to the books only for publishing), this book was naturally compiled based on real drilling constructions. After my first reading, I think the book, which is a monograph on continental scientific drilling, is worth reading, learning, and thinking. "Practice makes genuine knowledge" and the key point is "to make". How to raise perceptual knowledge to rational knowledge through scientific thinking should be seriously considered. Science and technology are for real and shall not permit any impetuousness and dishonesty. We are glad of the success of CCSD-1 Well which has promoted the development of scientific drilling. This must be affirmed. However, in the course of scientific and technological development, it is only one link.

In conclusion, it should be noted that all our achievements and innovations of today are made on the basis of our predecessors, without which we could not make any achievements. For this, we have no reason to become arrogant. "Modesty helps one to go forward, whereas conceit makes one lag behind." That is what I am willing to share with you.

Beijing, January 1, 2015

Li Shizhong
Professor, China University of Geosciences (Beijing)

Preface

"Going up to the space, reaching the interior Earth, entering into the sea" are three magnificent feats of human beings to challenge the natural world to expand living space. For thousands of years, human beings have achieved great success in going up to space and entering into the sea, while still struggling hard with the exploration of the interior Earth. Scientific drilling is a great project with epoch-making significance in contemporary Earth Science research. Through the direct observation of the lithosphere by scientific drilling, the material composition and structure of the continental crust can be explained, results of geophysical telemetry of the deep Earth can be rectified, the deep Earth fluids system and geothermal structure can be studied, the distribution and incubation conditions of subsurface microbes can be explored, and then the development of deep Earth geology can be promoted, and all these are helpful to solve a series of fundamental scientific problems, such as global climate change, law of earthquakes and biological origin, etc. In conclusion, scientific drilling, which is of very important significance to solve the problems of resources, disasters, and environment during the development of human society, is also a major scientific project which can bring along the development of relevant engineering technology, and is another magnificent challenge toward the Earth after man's landing on the moon.

The China Continental Scientific Drilling (CCSD) Project is a major national science project listed in the ninth Five-Year Plan (1996–2000), as well as a project of the International Continental Scientific Drilling Program (ICDP) currently being implemented. The main task of the project is to drill a 5,000-m-deep well for continuous directional cores, rock, and fluid samples, and in situ downhole observation data in Dabie-Sulu ultrahigh-pressure metamorphic belt, a global significant convergent plate boundary, to make comprehensive geophysical surveys, identify the material composition and structure of the continental orogenic belt, and reveal the formation and exhumation mechanism of the ultrahigh-pressure metamorphic belt. The 5,000-m-deep well will be built as a long-term underground observation and experimental base.

With tremendous technical difficulties, it is the first time in our country to construct a 5,000-m-deep well in hard crystalline rocks for full-hole continuous coring, which is one of the most difficult drilling constructions in the world as well. For nearly four years, from the project feasibility study, drilling technical personnel of our country have played their wisdom and creativeness and overcome numerous difficulties during the stages of engineering design, drilling construction, research and application of the key technologies, and solved construction problems until the successful completion of the project. While absorbing the world's advanced technology on scientific drilling, they successfully created and applied a series of new technologies and equipment, formed the new scientific drilling technology system with Chinese characteristics, which withstood the severe test of hard rocks and complex formations in Sulu ultrahigh-pressure metamorphic belt, completed CCSD-1 Well with high quality and efficiency and at low cost, and made outstanding important engineering achievements. These achievements greatly promoted the progress of scientific drilling technology, as well as exploration drilling for energy and resources. The success of CCSD-1 Well not only showed that deep drilling technology in our country had obtained great progress, but also greatly enhanced China's international standing in drilling technology.

The implementation of the CCSD Project is the start of the magnificent plan of "reaching the interior earth" in China, with initiative in the history of the Earth Science research in the country. In recent years, the environmental scientific drilling and the Cretaceous scientific drilling have been started in China, and the ultra-deep scientific drilling for oil and gas resources and deep solid mineral resources will be gradually started. A new situation in Earth Science has been formed; marking China's new step that has made it from a large geoscience country to a powerful geoscience country, which is bound to make impacts on the harmonious development of the society and nature and the modernization of our country.

This book comprehensively describes the drilling technologies of CCSD-1 Well, brings together various data and information accumulated in the process of drilling, and shows the latest technologies and research achievements of scientific drilling in China. The main authors of the book all used to take the major tasks at the construction site as technical backbone, and this book is a summary of their creative thinking in drilling practice, and the crystallization of their wisdom.

Veteran drilling experts threw all their energy into the project. They laid a very strong technical foundation for the start of the project. The project gathered a large number of outstanding middle-aged and young technical experts; some of them have extensive management experience; some have solid theoretical foundation and research experiences of many years, being creative and good at solving the new problems arisen during the construction; some have worked throughout the year at drill sites for technical services and production supervision and been adept in solving complex problems happened at the drill sites; and some just graduated from schools, being quick thinking and enthusiastic, with new professional knowledge, especially modern data processing technology, and brought fresh air to the drill site.

In order to enable the project to come up to international professional standards, the majority of the construction staff received training from the International Continental Scientific Drilling Program (ICDP). It is their hard work that offered the book with a wealth of original materials.

It has to be particularly noted that Liu Guangzhi, an academician of the Chinese Academy of Engineering, has led and organized the continental scientific drilling in China for decades. He first introduced the recent progress in this field and advocated the implementation of China's Continental Scientific Drilling Project; organized the planning of scientific drilling program and the discussions of technical program in the country, compiled a Series of Exploration of the Deep Continental Crust (eight volumes), cultivated a great number of middle-aged and young scientific and technological personnel engaged in scientific drilling, and therefore laid a solid technical foundation for the success of CCSD-1 Well.

Dedicated help and support to CCSD-1 Well project were given from the Institute of Exploration Techniques of CAGS, Beijing Institute of Exploration Engineering, the Institute of Exploration Technology of CAGS, China University of Geosciences (Wuhan), China University of Geosciences (Beijing), Construction Engineering College of Jilin University, Chengdu University of Technology, Zhongyuan Petroleum Exploration Bureau of Sinopec Group, Shengli Petroleum Administration Bureau of Sinopec Group, Dezhou Oil Drilling Institute of the Academy of Oil Exploration and Development, and Drilling Research Institute of CNPC and China University of Petroleum (Beijing). The Department of Land and Resources of Jiangsu Province and Geology and Mineral Exploration Bureau of Jiangsu Province Lianyungang City, Donghai County, and other circles paid great attention to the project. The authors would like to express their heartfelt thanks to the Drilling Engineering Advisory Committee and the experts from all fields, for their suggestions and great efforts to the drilling engineering. The members of the Drilling Engineering Advisory Committee are as follows:

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This book was written by Wang Da, Zhang Wei, Zhang Xiaoxi, Zhao Guolong, Zuo Ruqiang, Ni Jialu, Yang Gansheng, Jia Jun, Yang Kaihua, Zhu Yongyi, Xie Wenwei, Zhu Wenjian, Zhang Peifeng, Fan Lasheng, Ye Jianliang, and Wang Yongping. After the completion of the first draft, the book was revised and unified by Wang Da, Fan Lasheng, and Zhu Wenjian.

Beijing, January 17, 2015 Da Wang