Conclusions

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Under the care and support of the leaders and experts from the executing entity of the Nanjing Center, China Geological Survey, and the undertaking entity of Zhejiang Institute of Geological Survey, the project team of the *Regional Geological and Mineral Surveys of Hanggai Map sheet (H50E009022), Xianxia Map sheet (H50E010022) and Chuancun Map sheet (H50E010023) in Zhejiang (1:50,000)* has worked hard and assiduously for more than three years and successfully completed various tasks. Based on the systematic analysis of this survey and previous data, abundant geological data have been obtained about the strata, structures, intrusives, volcanic rocks, and mineral deposits, together with a number of research results. The most outstanding results among them were the establishment of the "Standard Cross Section of the Lower Yangtze Region in the Upper Ordovician Hirnantian" of Hanggai Town, Anji County, Zhejiang, the establishment of ten graptolithic zones in the Ordovician-Silurian, the first discovery of the sponge fossils in the Late Ordovician Hirnantian, and the development of the Late Ordovician volcanic events. These results not only provide basic and detailed original data, but also improved the research level of related professional fields in the survey area, Zhejiang Province and South China. It would provide abundant evidences of biological evolution and volcanic events for further stratigraphic study and the Caledonian tectonic event studies.

The project results have been converted and applied in geological relic planning and protection, scientific research, geological science popularization, college teaching practice, mineral exploration guidance, and other aspects and have achieved significant social benefits. The project achievements were rated as the top ten geological achievements of the "12th Five-year plan" in Zhejiang Province. The "standard cross section" has been listed as a provincial geological relic for protection by the Anji Municipal Land Resources Bureau and People's Government of Hanggai Town. From April 2013 to now, researchers from the Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, Key Laboratory of Resource Stratigraphy and Paleogeography, Chinese Academy of Sciences, the National Museum of Wales, Academician and Expert Workstation of Nuclear Engineering Jingxiang Construction Group Co., Ltd., have repeatedly investigated and studied the sedimentary stratigraphic sections in the surveyed area. The School of Earth Sciences, Zhejiang University, has organized students to conduct field internships in the investigation area many times and obtained good practice teaching achievements. The Hangzhou Daily, Xiaoshan Daily, and Huzhou Aishan Primary School have organized several batches of primary and secondary school students to carry out geological science popularization activities in typical sections and important fossil sites found in the project and greatly improved the general public's awareness of geological work. Up till now, the "standard cross section" has become an important base for geological science popularization education of the Hangzhou Newspaper Group.

5.1 Innovative Results

5.1.1 Established the "Standard Cross Section of the Lower Yangtze Region of the Upper Ordovician Hirnantian" in Hanggai, Anji County, Zhejiang

Through the comprehensive study and analysis of multiple strata, including lithostratigraphy, sequence stratigraphy, biostratigraphy, chronostratigraphy and chemical strata, and the discussion of sedimentary environment, as well as the comprehensive comparison with stratotype section, the standard cross section of the lower Yangtze Region of the Upper Ordovician Hirnantian and the typical section of the boundary between the Ordovician and the Silurian are established for the first time. It provides a reference for the study of regional stratigraphic correlation and greatly improves the level of stratigraphic research in the lower Yangtze Region.

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In November 2015, the All China Commission of Stratigraphy organized relevant academician experts to conduct field investigation and demonstration of the declared "Standard Section of the Lower Yangtze Region in the Upper Ordovician Hirnantian" of Hanggai, Anji County, Zhejiang. At the same time, the Commission advised Zhejiang Provincial Department of Land and Resources, the People's Government of Anji County, and Zhejiang Institute of Geological Survey to incorporate the protection and research of Hanggai "Standard Section" in Anji County into the planning of geological environment protection and ecological construction, and further strengthen the protection and utilization of the section and scientific research. The Commission believed that the following innovative results had been achieved in the section:

1. There was a complete outcropping of the Hirnantian and Ordovician-Silurian boundary strata in the Hanggai "Standard Section" of Anji, Zhejiang Province. Cyclic deposition of graptolite shale and fine-grained clastic rock with a thickness of more than 360 m developed and the chemical stratigraphic studies of carbon isotopes have been carried out. No structural deformation is developed near the main boundaries, and the geological events and biological sequences of the Hirnantian have been completely recorded, which meet the requirements of establishing the standard stratigraphic section of the Hirnantian and the Ordovician-Silurian boundaries in the Lower Yangtze region.
2. The section is rich in well-preserved fossils. Identified in the Upper Ordovician Katian-Hirnantian and the Lower Silurian Rhuddanian strata were six graptolite zones, including *Dicellograptus complexus, Paraothograptus pacificus, Normalograptus extraordinarius, Normalograptus persculptus, Akidograptus ascensus, Parakidograptus acuminatus*, and 1 (one) crustacean fauna *Songxites–Aegiromenella*, as well as diverse graptoliths, Chitinozoans, sponges, trilobites, gastropods, brachiopoda, cephalopods, and other phylum fossils.
3. Rich sponge fauna (more than 10 genera and species) was first discovered in the Hirnantian, opening an important window for further understanding the global biosphere appearance of the Hirnantian and the evolution of sponge organisms after the Cambrian life explosion.

5.1.2 Fossils of Sponges in the Upper Ordovician Hirnantian Have Been Discovered for the First Time

Throughout the field geological investigation, a large number of sponge fossils were found in the special lithologic layer of black carbonaceous shale in the middle of the Wenchang Formation of the Upper Ordovician Hirnantian in the survey area. It is the first discovery of this contemporaneous horizon, which has important research significance in the following three aspects. (1) It is the initial discovery in the strata during this period, with great research value. (2) These sponges are of the Burgess Shale type, which was previously believed to have died out in the first major extinction event at the early stage of the Late Ordovician Hirnantian, while the sponges in the survey area were symbiotic association with the *Normalograptus persculptus* graptolith belt at the end of the Hirnantian, showing that it lived till the end of the Hirnantian and did not die out during the glacial period. (3) These sponges are generally growing in an oxygen-rich environment, while the sponges in the survey area are found in the carbonaceous shale that indicated an oxygen-deficient environment. It is suggested that the survey area was in a very special paleogeographic environment during that period, having important research significance in paleoecology, bio-paleogeography, and evolutionary paleontology.

Through the follow-up study of the Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, more than 75 species of sponge fossils in the section have been identified so far, significantly exceeding the total number of sponge genera collected over 100 years in the famous Cambrian burgess shale in Canada. It is the most abundant and diverse sponge fauna found during the geological history, revealing that the residual seafloor after the great catastrophe was not as quiet and desolate as previously thought, but still had abundant biological reproduction.

5.2 Other Results

5.2.1 Strata

(1) Stratigraphic unit framework is more accurately determined

Through the geological survey and combining with the foundation of predecessors, the stratigraphic units in the survey area were determined systematically. A total of 45 stratigraphic units were divided, including 19 formations and 26 members. The fundamental lithostratigraphy in the stratigraphic units was comprehensively studied, in combination with biological, sequence, geochronological and event stratigraphy, and the stratigraphic division and correlation of the Ordovician-Silurian strata were mainly carried out, which were divided into 8 second-order sequences and 25 third-order sequences.

(2) Ten graptolithic biobelts of the Ordovician-Silurian have been identified

The Ordovician-Silurian biostratigraphy has made great progress and breakthrough, and 10 graptoliths, and 1 fauna have been identified from bottom to top. Among them:

two graptolite zones of the Ningguo Formation (*Acrograptus ellesae* belt and *Nicholsonograptus fasciculatus* belt).
two graptolite zones of the Hule Formation (*Pterograptus elegans* belt and *Hustedograptus teretiusculus* belt).
two graptolite zones of the Changwu Formation (*Dicellograptus Complexus* belt and *Paraothograptus pacificus* belt).
two graptolite zones of the Wenchang Formation (*Normalograptus extraordinarius* belt and *Normalograptus persculptus* belt); in addition, 1 Chitinozoans—Wuningensis Songxites, Metacrinus, etc. (*Songxites* + *Aegiromenella*) fauna.
two graptolite zones of the Xiaxiang Formation (*Akidograptus ascensus* belt and *Parakidograptus acuminatus* belt).

(3) Fossils of other creatures from the Cambrian-Ordovician have been discovered

In the Late Cambrian–Early Ordovician Xiyangshan Formation, a *Lotagnostus americanus* was found. Conodonts were found in the Late Ordovician Yanwashan Formation, and 8 trilobites of genus and species were found in the bottom of the Late Ordovician Huangnigang Formation. The discovery of these fossils provides paleontological evidence for the exploration of the sedimentary environment, as well as original data for the subsequent biological research in the northwestern Zhejiang Province.

5.2.2 Intrusives

(1) A systematic investigation and classification of intrusives

The investigation and classification of the complex plutons, such as the Ma'anshan, Tangshe, Xianxia, Tonglizhuang, Wushanguan, and Zhinanshan-Dongkeng, were carried out. The features of the size, spatial and temporal distribution, contact relationships and rock type of the intrusives were well identified. It is determined that the intrusives in the survey area are mainly composed of monzonite, syenogranite, quartz monzonite, quartz syenite (porphyry), and the vein rocks are mainly composed of granitic rocks, pegmatite, diabase, and diorite porphyrite.

(2) A framework of regional tectonic–magmatic–thermochronology was established

Based on the zircon U–Pb geochronology and the rock geochemical characteristics, the tectonic-magmatic-thermochronology framework of three magmatic stages of the Cretaceous in the area was established, followed by K_1^1 (145.1–136.3 Ma), K_1^2 (133.9–125.0 Ma), and K_1^3 (130.5–127.7 Ma). The intrusive age of the vein rocks was determinate as 130.3–127.4 Ma.

The intrusion ages of the Yanshanian intrusives in northwestern Zhejiang and its adjacent area are mainly Middle Jurassic to Early Cretaceous (168–124 Ma) and mainly concentrated at 168–163 Ma, 150–147 Ma and 142–124 Ma.

(3) The series of intrusive rocks–volcanic intrusive rocks–(sub) volcanic rocks are divided and compared

Through a comparative study of the petrological, geochemical, and geochronological features of the intrusives in each period, the intrusives in the survey area are divided into two series of intrusive rocks and volcanic intrusive rocks, which were compared synthetically together with subvolcanic rocks, in order to discuss the source of magma, tectonic environment, intrusive mechanism and mineralization.

It is proposed that the intrusive rocks, volcanic intrusive rocks, and (sub) volcanic rocks in the survey area were all formed in the extensional environment that followed subduction orogeny in the Early Cretaceous. The early magmatism is dominated by differentiation crystallization and the late stage may be dominated by partial melting. The magmatic source of the intrusive rocks is dominated by the reconstruction of crustal materials in the ancient Jiangnan orogenic belt. The magmatic source areas of volcanic intrusive rock series and (sub) volcanic rock series may involve some lithospheric mantle materials of the Yangtze block. The igneous rocks in the survey area may be emplaced and formed successively by high degree of crystallization of magma derived from the remelting of crustal material in the eastern part of the ancient Jiangnan orogenic belt induced by the ascent of lithospheric mantle magma of the Yangtze block in the extensional and tensile tectonic

environment after subduction orogeny in the Early Cretaceous.

5.2.3 Volcanic Rocks

(1) Volcanic lithology and lithofacies are systematically divided

The Mesozoic volcanic rocks in the survey area were analyzed by the survey method of "volcanic strata—lithologic lithofacies—volcanic structure." The volcanic lithology can be divided into 4 categories and 13 subcategories, and volcanic facies can be grouped into eight types: explosive facies (fallout facies, clastic flow facies, surging facies), eruption-sedimentary facies, invasion overflow facies, explosive spill facies, eruptive spill facies, volcanic debris flow facies, volcanic vent facies, and subvolcanic rock facies. The field identification marks of volcanic facies were established, which provided preliminarily study of the Mesozoic volcanic rocks in northwestern Zhejiang Province.

(2) The evidence of rhythmic division and geochronology of volcanic eruption was determined

The survey area was divided into four volcanic eruption rhythms. The first eruption rhythm is mainly composed of the evolution of clastic flow accumulation facies (local sandwiched eruption-sedimentary facies) → fallout accumulation facies → eruption-sedimentary facies. The second eruption rhythm primarily consists of volcanic debris flow facies (local) → clastic flow accumulation facies → invasion overflow facies → eruptive spill facies → explosion spill facies → subvolcanic rock facies. The third includes clastic flow accumulation facies (locally intercalated eruption-sedimentary facies) → eruption-sedimentary facies → subvolcanic rock facies, while the fourth is mainly made of eruptive spill facies.

The zircon U–Pb isotope dating provides geochronological evidence for each volcanic eruption rhythm, restricting the volcanic eruption time of the Area to be in the range of 135.1–125.4 Ma in the Early Cretaceous.

(3) The volcanic edifice is divided

According to the control of regional faults on volcanic edifices and the features of volcanic edifice assemblage and volcanic lithofacies assemblage, the grades and types of volcanic structures are classified. The volcanic edifice in the region is divided into 1 Tianmu Mount volcanic depression, 5 (revived) calderas in Yangtianping, Tianhuangping, Changlongshan-Linjiatang, East Tianmu Mount-Caotanggang, and Yaotianfan, and 6 dome-shaped volcanoes in West Tianmu Mount—Longwangshan, South Tianmu Mount, Nanyushan, Shifo Temple, Dashulin and Wuguishan. A number of lateral craters of different sizes were also delineated in the dome volcano. The prioritized description was focused on the typical volcanic edifices of 4 calderas follow by Yangtianping, Tianhuangping, Changlongshan-Linjiatang, East Tianmu Mount-Caotanggang, and three dome-shaped volcanoes follow by West Tianmu Mount-Longwangshan, South Tianmu Mount and Dashulin.

5.2.4 Structure

(1) The structural traces of fold and fault are systematically investigated

Through the investigation of morphology, kinematics, and dynamics, the fold system in the survey area is divided into three stages: Caledonian, Early Indosinian, and Late Indosinian. In Caledonian, the archetype of the equally wide and gentle fold of the Wangjia-Tangshe anticline in the near EW trending was formed. In the Early Indosinian, a large baffle-type fold system was formed in the northeast direction, significantly controlling the main structural framework of the investigation area. In the Late Indosinian, a mainly straddling and relatively small and weak NW-strike fold was formed.

The fault system in the survey area is divided into four groups: EW trending, NE trending, NNE trending, and NW trending. The early basement thrust faults were near EW or NEE trending. In the middle stage, the NE-trending basement thrust faults were activated multistage in the later stage; NW-trending faults formed later or at the same time with NE-trending basement faults and most were transverse faults which cut folds. Late NNE-trending faults are dominated by left-lateral shear. The surface near EW-trending brittle fault was formed in the most recent period, mostly brittle fractures.

(2) The relationship between structure and formation of rocks, ore deposits, and basin is discussed

NE-trending basement faults control the outcrop and distribution of plutons in the survey area. The fractures closely related to ore mineralization are NE-trending and EW-trending faults, and NE-trending faults are mostly rock and ore conducting structures, while NW-trending faults are mostly ore-bearing structures. The large NE-trending fold system controls and forms the prototype of the Tianmu

Mount volcanic basin, which interacts with the near EW-trending concealed basement faults and NE-trending basement faults, resulting in the subsidence fault depression and formation of the volcanic basin.

(3) The development history of the structure is studied, and the evolution model is established

The survey area is located in the southeastern margin of the Yangtze block and has undergone four tectonic evolution stages, including the epicontinental overburden orogeny of the Chengjiang-Caledonian, the Indosinian intracontinental orogeny, the Yanshanian active continental margin, and the Himalayan tectonic uplift. In the Chengjiang-Caledonian, the Area has experienced three evolutionary stages: the Early Nanhuaian continental margin rift basin, the Late Nanhuaian–early stage of the Late Ordovician passive continental margin basin, and the late stage of the Late Ordovician–Early Silurian peripheral foreland basin, so that the Yangtze block and the Cathaysian orogenic system merged into an unified continent. In the Indosinian, the Area was uplifted and exposed, forming the NE blocking fold system and NE basement fault system, which greatly influenced and controlled the tectonic features of the surveyed area. Due to the continuous subduction of the paleo-Pacific plate into the South China Block, the Yanshanian survey area entered the active continental margin stage, characterized by intense magmatic activities and mineralization. In the Himalayan, the survey area was in a relatively quiet interval, dominated by uneven differential movement.

5.2.5 Database

A series of maps including geological map (1:50,000), geological and mineral resources map, volcanic lithofacies structure map, ore-bearing formations and structural map and metallogenic elements and metallogenic prediction maps of typical deposits have been prepared. By means of digital regional geological survey, the databases of the raw data have been established, including freehand field map library (1:25,000), total field map library, original data distribution map library and section database, stream sediment survey database (1:50,000), as well as the manuscript database and the result database. All the data formats conform to related specifications.

5.3 Problems and Suggestions

The geological structure of the survey area is complex. The strata, structure, igneous rocks, and mineral resources are all relatively developed. Due to the limited time and funds, there are still some basic and key geological problems that restrict the ore prospecting, which need to be further studied and solved:

1. Due to poor outcrop, strong alteration, and other reasons, the control accuracy of the Nanhuaian in this work is not enough.
2. The Ordovician-Silurian stratigraphic cross section in the survey area is an ideal research area for biostratigraphy. Although 10 graptoliths and 1 fauna have been found in this work, more graptoliths cannot be found without enough funds and time. Further research should be carried out and comparison with Hirnantian stratotype section should be made. It is suggested that these sections should be protected as typical sections of the Ordovician and Silurian.
3. The complex structure of the survey area experienced tectonic evolution during multistages of the Caledonian, the Early Indosinian, the Late Indosinian, the Yanshanian, and the Himalayan. Although this work was carried out the investigations and studies on the distribution pattern and mechanical properties of important fold and fault structures, there is still a lack of detailed research on the superposition and combination of structures, and further investigation should be conducted.
4. In this work, the important mineral source strata and igneous rocks in the survey area have been preliminarily divided, but the metallogenic strata in the stratigraphic unit have not been precisely determined. It is not clear about the difference of intrusives and structures on mineralization, which needs further investigation and study.
5. The survey area has a desired metallogenic prospecting. Due to the limitation of funds, this work is less invested in mineral exploration to ensure regional geological survey, and only the Hanggai stream sediment measurement was made. The results only show a very small number of important anomalies and mineral occurrences (spots) inspection with a preliminary inspection level. In the following work, regional geophysical and geochemical prospecting, mineral inspection and comprehensive research should be strengthened to provide theoretical and technical support for regional prospecting breakthroughs.

During the project, the survey team received strong support and help from many leaders and experts from the Nanjing Center, China Geological Survey and the Zhejiang Institute of Geological Survey. Prof. Rixiang Gong, Kongzhong Wang, and Zhongda Chen have guided the project team in the fieldwork for many times. In order to compile the report, the experts including Prof. Yanjie Zhang

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Due to the limited knowledge and time, there are inevitably some problems and deficiencies in this book, which we sincerely wish readers to criticize and correct.