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**University of the Witwatersrand
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**GEOLOGICAL CHARACTERISTICS OF PGE-BEARING
LAYERED INTRUSIONS IN SOUTHWEST SICHUAN
PROVINCE, CHINA**

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by

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GEOLOGICAL CHARACTERISTICS OF PGE-BEARING LAYERED INTRUSIONS IN SOUTHWEST SICHUAN PROVINCE, CHINA

ABSTRACT

A number of platinum-group-element (PGE-bearing), layered, ultramafic-mafic intrusions in the Pan-Xi and Danba areas of the southwest Sichuan Province of China have been investigated. The two study areas are located, respectively, in the central and northern parts of the Kangding Axis on the western margin of the Yangtze Platform, a region geologically distinguished by late- Archaean to late-Proterozoic basement and by stable sedimentary sequences. The Yangtze Platform was re-activated by 400-250 Ma Hercynian-Indosinian orogeny and magmatism, resulting in widespread intrusion of igneous rocks.

Six ultramafic-mafic intrusions, emplaced during the orogeny at about 350-250 Ma, include the Badong, Xinjie, Panzhihua, Lufangqing and Dayanzi layered bodies in the Pan-Xi area and the Yangliuping body in the Danba area. These intrusions occur in a north-south striking belt, which is approximately 500 km long and 30 km wide. The Panzhihua and Xinjie intrusions are characterized by igneous layering, with the main rock types, from bottom to top of individual cycles, consisting of peridotite, pyroxenite and gabbro, suggesting that the rocks were derived from mafic magma differentiation. The other four intrusions are dominated by pyroxenite and gabbro, and are less clearly layered. The intrusions were emplaced during an orogenic episode, which is believed to have occurred approximately 350-250 Ma ago.

Three varieties of intrusion-related PGE mineralization were identified. These include: (1) magmatically layered Cu-Ni-PGE (Xinjie); (2) late- or post-magmatic hydrothermal Cu-Ni-PGE mineralization (Yangliuping); and (3) fault-related hydrothermally altered Cu-Ni-PGE mineralization (Badong, Dayanzi, Lufangqing). The country rock and portions of the intrusive complexes of types 2 and 3 above are characterized by hydrothermal alteration, manifested by silicification, serpentinization and carbonatization along the contact zones. The main ore minerals associated with the PGEs include chalcopyrite, pyrrhotite and pyrite. The PGEs occur mainly in the form of sperrylite (PtAs_2), borovskite (PdSbTe), merenskyite-moncheite (Pd,PtTe_2) and native Pt. It is suggested that the PGE mineralization in the Pan-Xi and Danba areas was associated with magmatic and late- or post-magmatic hydrothermal processes.

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INTRODUCTION

Platinum-group-element (PGE-bearing), ultramafic-mafic intrusions and associated PGE ore deposits are becoming increasingly important topics of research and targets for mineral exploration due to the sustained demand for PGE metals and rising prices in recent years. It is estimated that the consumption of Pt in the jewellery market in China alone was more than 1.2 million ounces in 2001 and is projected to increase in 2002. Known PGE metals in China are associated mainly with magmatic Cu-Co-Ni deposits, such as the Jinchuan deposit of the Gansu Province and the super-large V-Ti magnetite deposits of the Pan-Xi Layered Complex of the Sichuan Province. Current production of Pt (<0.5 million ounces) in China cannot satisfy the market requirements. Consequently, there has been a concerted drive to locate and understand PGE-bearing intrusions in China with a view to the economic exploitation of possible PGE deposits. PGE geochemical anomalies have recently been found in the Pan-Xi Layered Complex, and geological research and regional exploration for PGE deposits in the area are actively being carried out by Chinese geologists.

The Bushveld Complex (*c.* 2060 Ma) in South Africa is the largest PGE-bearing layered ultramafic-mafic complex in the world and has been studied by geoscientists and exploited by the mining industry for over 75 years. More than 75% of the world's PGE resources are hosted by this remarkable complex and its current production of PGE metals equates to almost half of the total world PGE metal production. As the foremost producer of PGE metals, South Africa has developed outstanding expertise in both PGE research and in exploration and mining. This has led to a joint research project, involving geological teams from China and South Africa, whose aim it is to investigate PGE-bearing intrusions in both these countries.

Early in 2001, the proposed three-year project entitled "A co-operative study of PGE-bearing layered intrusives, between the People's Republic of China and the Republic of South Africa" was approved for funding by the National Research Foundation (NRF), South Africa as well as by the Division of Asia and Africa of the Department of International Co-operation, Ministry of Science and Technology, People's Republic of China and the Chinese Academy of Sciences. In June 2001, the South African team was invited by their Chinese partners to participate in a field excursion to examine PGE-bearing ultramafic-mafic intrusions in the Sichuan Province of southwest China. The excursion, commenced in Chengdu (capital city of the Sichuan Province), and proceeded south to Panzhihua on the Jinsha River (upper Yangtze River). It then continued northwards to Danba on the River Dadu, before returning to Chengdu - a circular route covering a distance of more than 2500 km (Fig.1). Six PGE-bearing intrusions and their related ore deposits/prospects were examined during the excursion.

The aims of the field trip were to: (1) investigate the geological characteristics of the major PGE-bearing ultramafic-mafic intrusions in both the Danba and Pan-Xi areas; (2) collect samples for preliminary laboratory investigations; (3) select typical PGE-bearing intrusions and target areas for further study as part of the co-operative project; and (4) discuss a comprehensive research plan for the joint project. The Chinese team subsequently visited South Africa during October 2001 and an account of this trip as well as of projects arising from it will be presented in a further report.

This paper presents a summary of the field excursion to China emphasising the regional geology and the intrusion-related, PGE-bearing ore deposits and prospects.

GEOLOGICAL SETTING

The Chinese continent is composed of several geotectonic units in terms of stable platforms and mobile (fold) belts - a detailed description of which is beyond the scope of this paper. The regional map (Fig. 1) provides an indication that the PGE-bearing ultramafic-mafic intrusions examined lie close to the contact between the Yangtze Platform and the north-south trending Qinghai-Xizang-West Yunnan fold belt. The Danba intrusion is located on the east margin of the fold belt whereas the Panzhihua-Xichang (i.e., Pan-Xi) intrusions lie in the

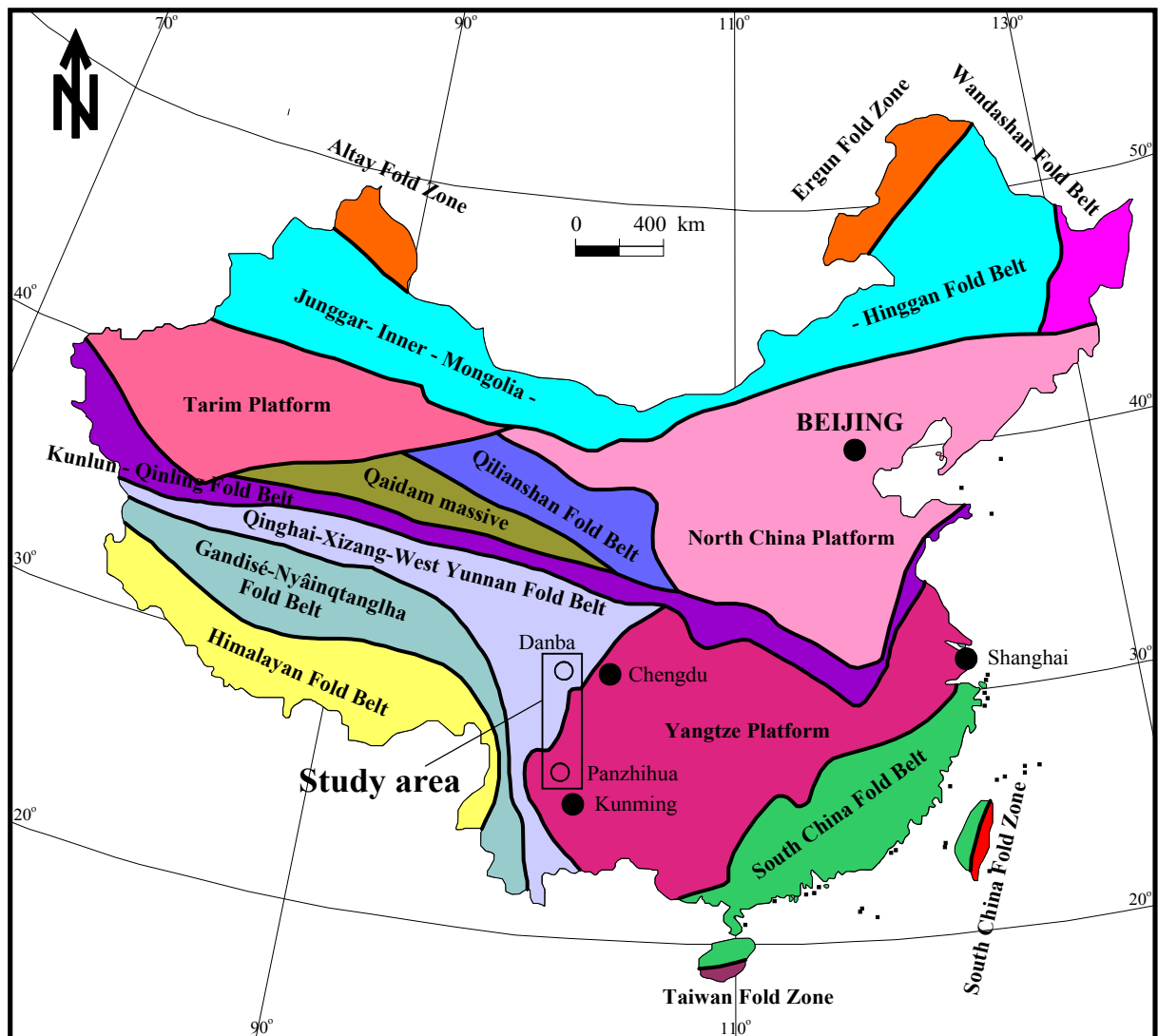


Figure 1: Geotectonic sketch map of China (modified after Ma et al., 1996), showing the position of the Panzhihua-Danba study areas.

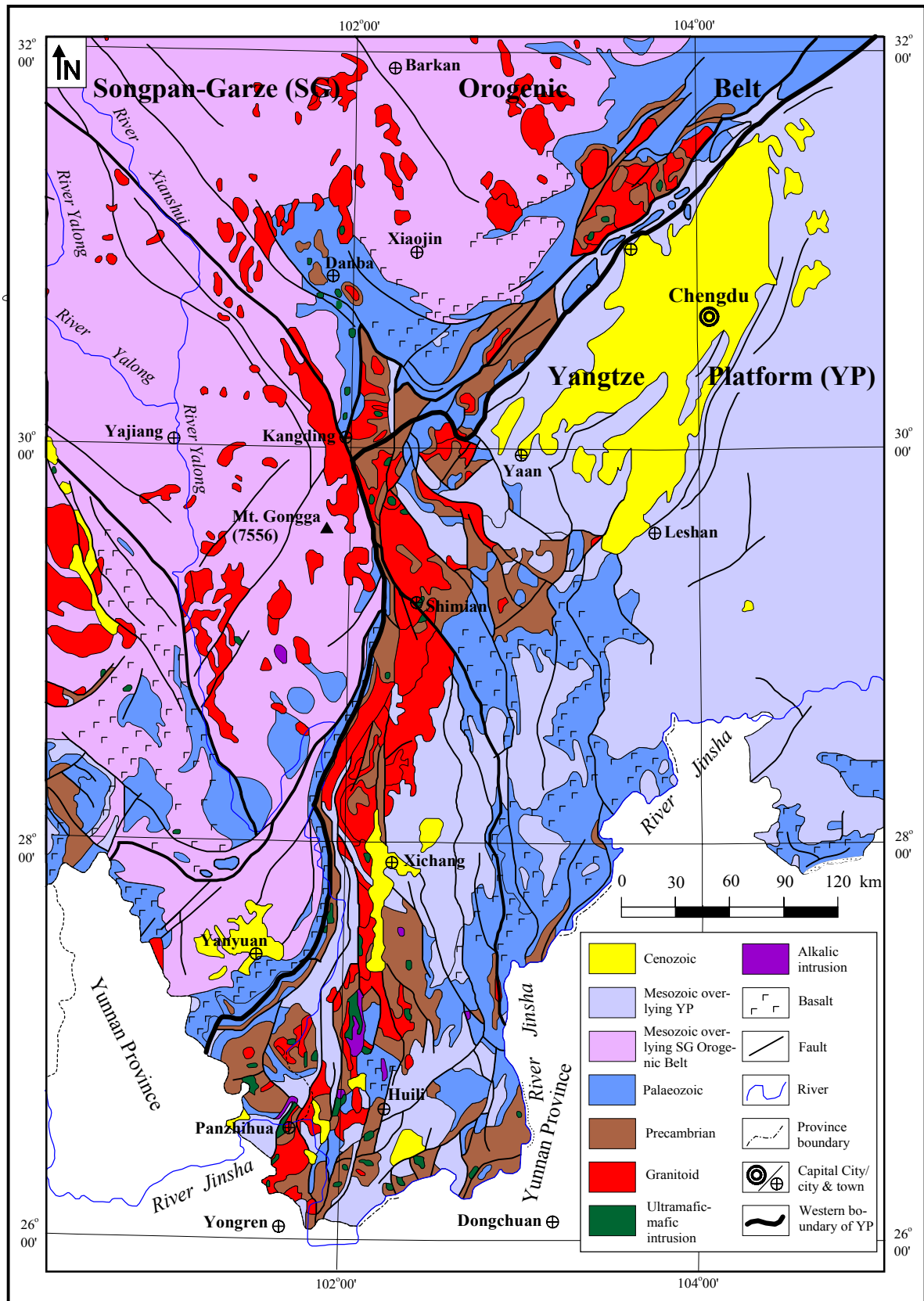


Figure 2: Simplified geological map showing the ultramafic-mafic intrusions in the Danba and Panzhihua-Xichang areas, southwest Sichuan Province (modified from MGMR, 1998). SG=Songpan-Garze Orogenic Belt, YP=Yangtze Platform.

western portion of the Yangtze Platform (Fig. 1). The Yangtze Platform is, in turn, separated from the Kunlun-Qinglin fold belt (a crustal subduction zone formed by multi-stage orogenies from 800 - 200 Ma), and is bordered by the Qinghai – Xizang - West Yunnan fold belt (a complex of Karakorum-Tanggula, Sanjiang and Songpan-Garze fold belts formed in the Indosinian and Yanshanian orogenies at 200 - 65 Ma) in the west (Fig. 1). In the southeast, the Yangtze Platform abuts against the South China, Caladonian (600 - 410 Ma) fold belt (Fig. 1). It was previously thought that the Yangtze Platform was formed during the Jinning orogenic episode (800 - 600 Ma), but some places (e.g., southern Sichuan) were stable after the Luliang orogenic episode (*c.* 1850 Ma - Ma et al., 1996). The platform is characterized by two structural basements (*viz.*, a late-Archaeon to early-Proterozoic crystalline basement and a middle- to late-Proterozoic folded basement). Both are overlain by a thick (>10000m), stable sedimentary cover sequence (GMGR, 1998).

The geotectonic units of the Danba and Pan-Xi areas form part of the Songpan-Garze orogenic belt and the Panzhihua-Xichang intracontinental rift belt (GMGR, 1998). The Songpan-Garze belt in western Sichuan occurs between the Jinshajiang ophiolitic melange and the Longmenshan-Xiaojinhe fault zones, and is part of the eastern Tethyan orogenic system. The orogenic belt is thought to have resulted from the Indosinian collision of the Yangtze Platform and the Qiangtang block (Li et al., 2001). It consists of parallel ophiolitic melange zones, volcanic island-arc zones, a fore-arc or inter-arc, flysch, accretionary wedge (P₂-T₃), and back-arc basin sediments. Numerous granitoids, which intruded the thick (up to 10000m) Triassic marine-facies flysch (comprising sandstones and slates, locally intercalated with volcanic rocks and carbonates), occur mostly in the central and southwestern portions of the belt as batholiths and stocks. Most of the granitoids are Hercynian-Indosinian in age. Regional, dynamic, low-grade greenschist facies metamorphism took place in the Indosinian period (whole-rock K-Ar age: 195-210 Ma, GMGR, 1998).

The Pan-Xi palaeorift region is located in southwest Sichuan Province at 26°00' - 28°30'N and 101°30' - 103°30'E. Geotectonically, this domain is situated on the western margin of the Yangtze Platform and constitutes the boundary of the Xizhang-West Yunnan fold belt in the west (Fig. 1). It is a subtectonic unit of the Kang-Dian foreland uplift belt (GMGR, 1998). The rift comprises an area from Mianning in the north to Dukou in the south and is bordered by the Jinhe-Qinghe fault zone in the west and the Xiaojiang fault zone in the east (Chinese Members of Co-operative Geological Group of China and Japan in the Pan-Xi region - CMGJ, 1988).

The regional geology of the Danba and Pan-Xi areas is characterized by uplift-cored Precambrian metamorphosed basement along the margin of the Yangtze Platform and the Songpan-Garze orogenic belt. Palaeozoic-Mesozoic cover sediments are distributed along the basement. Deep-seated and second-order faults, striking in NNE, NS, NW, and NE directions, are well developed in the basement and cover sequences and change direction in the Kangding area (Fig. 2). Magmatic intrusions, including ultramafic-mafic to acidic in composition, and volcanic rocks (mainly Permian basalts) are extensively developed along the NS-, NE- and NW-striking faults and were extruded mainly during the Hercynian-Indosinian orogeny (*c.* 350-250 Ma). The regional metamorphism in the east (the Yangtze Platform), is not present in the cover sequence, but is well developed in the west (e.g., the Songpan-Garze orogenic belt, GRGM, 1998).

GEOLOGY IN THE PAN-XI AND DANBA AREAS

Pan-Xi area

The basement of the Pan-Xi rift comprises Precambrian (Middle-Later Proterozoic) metamorphic rocks which consist of the Dukou Complex and the Miyi Group as well as the Huili and the Yanbian Groups (CMCJ, 1988). The former two groups are composed of a variety of gneisses, schists, and metavolcanic rocks with minor granulites and marbles, and have undergone moderate- to high-grade metamorphism varying from amphibolite to granulite facies. By contrast, the Huili and the Yanbian Groups are composed of metasedimentary and metavolcanic rocks (sandstone, dolomite, slate, phyllite, tuff, basalt and quartzite), which have been subjected to greenschist facies metamorphism (CMCJ, 1988). The whole-rock Rb-Sr isochrones for the Dukou Complex yielded ages between 1185 ± 50 and 1007 ± 20 Ma. The latter age was considered to record a migmatization event. The ages of two whole-rock Rb-Sr isochrones of the Miyi Group are around 1033 and 1045 Ma, respectively. These ages are considered to record major metamorphic events. The upper metamorphosed sandy rocks of the Huili Group yielded a whole-rock Rb-Sr isochron age of 907 ± 19 Ma, and the metavolcanic rocks of the lower Huili and the lower Yanbian Groups have whole-rock Rb-Sr isochron ages of around 1000 Ma, respectively. The protolithic rocks include: (1) a calc-alkalic series of gabbro-noritic, tonalitic, trondhjemitic and granitic rocks for the Dukou Complex; and (2) island-arc tholeiitic and alkaline basaltic rocks as well as greywacke, sandstone, pelitic and calcareous sediments for the Miyi Group.

Cover rocks of the Pan-Xi area comprise Sinian- to Tertiary-age marine and continental sediments. The Sinian sequence, including the Wusidaqiao and the Xiadong Groups, unconformably overlies the basement metamorphic rocks. The Wusidaqiao Group occurs mainly in the Xichang-Dechang and Baiposhan and Guangtoupou areas and is dominated by red sandstone and mega-coarse conglomerates, representing point bar and alluvial fan sedimentary facies. The Xiadong Group comprises marine sedimentary rocks, including coastal facies sandstone at the base as well as carbonate-platform facies dolomite and sea-basin dolomite with chert bands. The lower-Cambrian to middle-Ordovician marine limestone, shale, siltstone and sandstone only occur in the eastern part of the Kangdian Palaeozoic uplift block, whereas marine facies dolomite, limestone and chert bands from middle Devonian to lower Permian occur mainly in the western part of the Kangdian Palaeozoic uplift block. The upper Permian is characterized by the extensive eruption of Emeishan basalts throughout the whole area. The upper-Triassic sequence is composed of sandstone, conglomerate, shale and coal-bearing seams belonging to sedimentary facies of river-lake alluvial fans. The Jurassic-Cretaceous succession comprises block-subsiding clastic rocks, including sandstone, shale, limestone, conglomerate, siltstone, gypsum, arkose and arenite. These rocks form a large, composite, red basin characterized by five sedimentary cycles. Individual cycles begin with conglomerates or gravel-bearing sandstones and grade upwards into sandstones and mudstones, terminating with shales (CMCJ, 1988). The Cenozoic sediments, including Tertiary and Quaternary clastic rocks, were deposited in several terraces of different elevation.

Compression took place mainly during the Jinning orogenic cycle and gave rise to approximately EW-trending fold axes in the metamorphic basement rocks. The EW-striking folds are modified by and partly overlapped by the pre-Chengjiang tectonism. The cover folds have an approximate N-S strike direction. Thrusts were developed parallel to the N-S axis and faults display N-S, E-W, NW, NE and NNE-striking directions. The major regional N-S fault zones formed during the Precambrian and underwent multiple phases of shear-tension or

shear-compression. E-W-striking lithospheric fractures occur in the Xiaoguanhe fault zone, which controls Precambrian ultramafic intrusions. The arcuate Jinhe-Qinghe fault zone constitutes the western boundary of the Kangdian Palaeozoic uplift. This fault zone formed in late Hercynian-Indosinian times and controlled the eruption of the Emeishan basalts and the Triassic sedimentation (CMCJ, 1988). It appears that the ultramafic-mafic intrusions, syenite, alkaline granites and basalts are temporally and spatially associated with each other (Zhang et al., 1995). The igneous sequence “one series of the three geological units” implies that they were derived from the same magmatic source.

Danba area

The basement in the Danba area is composed of middle- to late-Proterozoic domains to the south and west of Danba. Rock types include migmatitic granites, gneisses and schists. Protoliths of these rocks are intermediate-to-mafic and intermediate-to-acid volcano-sedimentary rocks, which were subjected to amphibolite facies metamorphism (Li et al., 2000). The sedimentary cover sequences are Palaeozoic-to-Mesozoic in age and are mainly composed of quartzite, schist, gneisses, marble, phyllite, slate, carbonate rocks and metabasalts. These rocks were subjected to regional, dynamic, low-grade greenschist metamorphism.

The migmatized domains are typical of the area. Shear zones, parallel to sedimentary layers and, in particular, along contact zones between different lithological units, are well developed and are characterized by multiple-stage ductile-brittle shearing through the basement and cover sequences. Schists, gneisses and mylonites are also developed in and along the shear zones. Regional faults trend mainly NW-SE and N-S and displace sedimentary units. Superimposed folds are usually associated with fracture zones, demonstrating a complicated structural system related to regional multiple-stage tectonic movements. The magmatic activity encountered in the area resulted from the multiple-stage evolution during the Proterozoic to Cenozoic eras and is described below.

MAGMATISM AND ULTRAMAFIC-MAFIC INTRUSIONS

Intrusive and extrusive volcanic rocks of various ages are widespread in the Pan-Xi and Danba areas (Fig. 2). They can be divided into two major groups of the Jinning-Chengjiang and the Hercynian-Indosinian cycles, the latter representing a major period of regional magmatism. The Jinning-Chengjiang cycle commenced in the Precambrian with volcanic rocks occurring in the Miyi, Huili, Yanbian and Wusidaqiao Groups. Ultramafic-mafic intrusions were also well developed during this period. Four types of intrusions have been recognized : (1) schistose and serpentized peridotite; (2) schistose gabbro; (3) Cu-Ni bearing peridotite-gabbro; and (4) clusters of small intrusive bodies. Granitic intrusions are also locally developed in the cycle.

The Hercynian-Indosinian ultramafic-mafic intrusions have been divided into three stages. The first stage (1) is characterized by ultramafic-mafic intrusions containing Cu-Ni sulphides and platinum-palladium ore deposits. Most of the intrusions occur in the Northern Yunnan Province. In the Pan-Xi area, the Abulangdang, Tiangfang and Limahe plutons are also grouped into this stage, but the former two intrusions contain no mineralization and show more mafic features and less well-developed differentiation. The second stage (2) is dominated by layered ultramafic-mafic intrusions characterized by vanadium-titanium-magnetite ore bodies. These intrusions are separated into two types. In the east, the intrusions,

from north to south, include the Yangxiu, Taihe, Aqi, Xinmin, Wenchanggong, Badong, Cida, Xinjie, Binggu, Anningchun, Zhonggangou, Hongge and Pulong intrusions, which are better mineralised towards the south. The Malong, Panzhihua and Luobodi intrusions occur in the west. The third stage (3) is represented by the eruption of the Emeishan basalts, which occur mainly in the early Permian of the Pan-Xi area. Eruption is mainly subaerial, but marine eruptions are also found in the southern part of Yunnan Province. Mafic and alkalic dyke swarms are also associated with the eruption of the Emeishan basalts.

Acidic-alkalic magmatism in the Hercynian-Indosinian can be divided into two stages: (1) the Ailonghe granite and the Hongge and Taihe alkalic granites, and the Hongge syenite; (2) the Cida alkalic granite, the Dechang trachyte from Ertan, and the Miyi and Liushaxiang syenites, unconformably overlain by upper Triassic sediments (Bingnan Formation). The alkalic rocks are represented by the Daxiangping alkalic-ultramafic complex, the Dechang and the Maomaogou syenites, the Huili alkalic-ultramafic complex and the alkalic volcanic-plutonic rocks of Pusaya and Dukou. These intrusions constitute an alkalic belt of rocks stretching roughly N-S over a distance of more than 200 km.

The Yanshanian cycle is not well developed in the region. The mafic dykes (*c.* 191 Ma) were emplaced during the stage of basin subsidence. Some subvolcanic and hypabyssal alkaline bodies in Dukou may be also attributed to the Yanshanian cycle. In the late Yanshanian, the intrusion and eruption of acidic and alkalic volcanic rocks occur locally with the closure of the basin. In addition, during the Xishanian period, only a few lamprophyre dykes were emplaced along the marginal fractures zones of the Yanyuan fault-depression.

In the Danba area, magmatic plutons and volcanic rocks of the middle- to late-Proterozoic (U-Pb zircon ages of 847 ± 26 Ma to 916 ± 36 Ma - Li et al., 2000) outcrop as domains which were strongly migmatized. Palaeozoic magmatism is characterized by rift-related mafic volcanic eruptions and hypabyssal ultramafic-mafic intrusions, which were metamorphosed to amphibolite, uralitites, talcites and serpentinites. These metamorphosed ultramafic-mafic intrusions are associated with PGE mineralization and are considered to be late Variscan in age (Li et al., 2000). During Mesozoic-Cenozoic times, magmatic intrusions of mafic, acidic and peralkaline compositions were emplaced in the area and occur as batholiths and stocks. Mafic-to-acid dykes are also associated with the intrusions.

PGE-BEARING ULTRAMAFIC-MAFIC INTRUSIONS

Panzhihua V-Ti-Fe-PGE deposit

The Panzhihua V-Ti-Fe-PGE-bearing, layered, mafic intrusion is located in the most southerly portion of the Pan-Xi area at Panzhihua city. A super-large V-Ti-Fe deposit is currently being mined in the region by open pit methods (Fig. 3a). The mafic intrusion was emplaced into the Kangdian axis uplift along the NE-striking Panzhihua fault zone in the early Hercynian orogeny (Liang et al., 1998) and is 19 km long, 2 km wide and more than 2 km thick. The deepest borehole into the intrusion has reached a depth of 850 m. The body intruded the Sinian limestone (Danyin Formation). On the basis of strata in the hanging wall it is suggested that the intrusion is a middle-to-shallow seated magmatic complex formed at a depth of around 3 km. The intrusion is mainly composed of gabbro, with minor peridotite, dunite and anorthosite towards the top. Ultramafic rocks are rarely found and the intrusion is mafic in

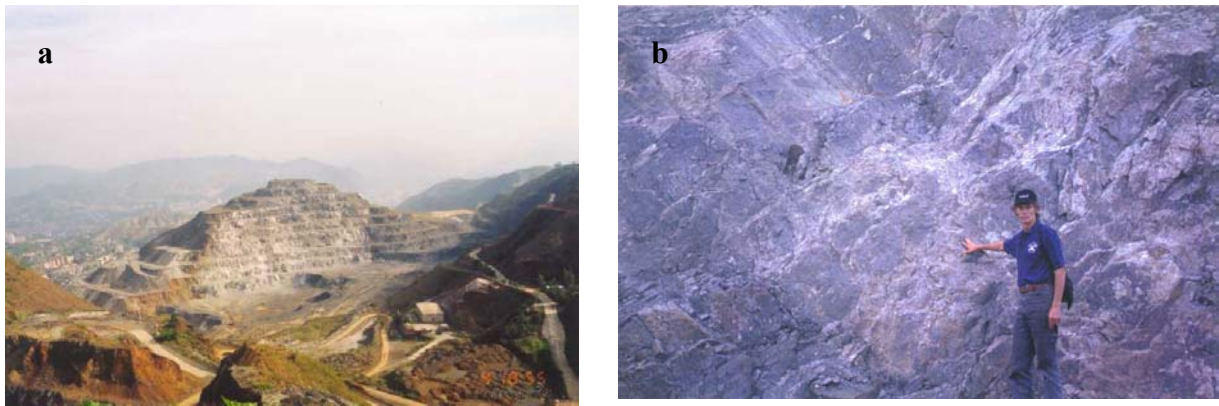


Figure 3: Photographs of (a) the Panzhihua open pit viewed to the north, and (b) gabbro-anorthosite layers seen in the intrusion looking to the northwest.

composition. Syenite-alkaline syenite, and granite-alkaline granites occur as dykes, sills and sheets overlying the intrusion as do the regionally extensive Permian Emeishan basalts. These rocks are considered to be co-magmatic or are in some way related to the mafic intrusions.

Layering within the intrusion is well developed (Fig. 3b). According to Liu et al. (1985), the Panzhihua mafic intrusion is comprised of two large cycles (I, II) and, from bottom to top, five lithological sub-facies (IA, IB, IC; IID, IIE). Cycle I is dominated, from base to top, by gabbro-titanomagnetite-anorthosite, and cycle II is mainly composed of olivine gabbro-apatite, titanomagnetite-bearing pyroxenite (peridotite) and amphibole gabbro. Rock-forming minerals and Fe-Ti oxides of the intrusions are mainly composed of V-Ti-magnetite, olivine, augite, hornblende, ilmenite, apatite and plagioclase. Titanomagnetite attains concentrations of up to 80% at the base of cycle I and decreases to <10% at the top of cycle II. By contrast, amphibole and plagioclase increase upwards from the bottom to the top of each cycle and lithological facies. An average chemical composition of the intrusions is as follows:

SiO₂ (42.83%), TiO₂ (4.17%), Al₂O₃ (15.78%), Fe₂O₃ (6.21%), FeO (8.81%), MnO (0.18%), MgO (5.14%), CaO (10.88%), K₂O (0.22%), Na₂O (2.93%), P₂O₅ (0.9%), Cr₂O₃ (0.008%), V₂O₅ (0.083%), Co (0.006%), Ni (0.011%).

SiO₂/MgO ratios usually increase from bottom to top and total Fe and Ti, V, Cr and Ni decrease upwards. P₂O₅ is enriched in the middle and top portions of the intrusion. The variation of chemical compositions is consistent with the change of mineral components upwards. As summarized by Fu (2001), isotopic age dates obtained by various methods range from 266-288 Ma (amphibole ⁴⁰Ar-³⁹Ar); 380 ± 20 Ma (whole rock Rb-Sr); and 210 ± 43-282 Ma (whole rock Sm-Nd). Taking into account geological relationships, it is probable that the intrusion was emplaced during the Hercynian.

Nine ore bodies (magnetite seams) occur as layers in the gabbro. The eighth seam, near the bottom of the sequence, occurs in dark gabbro and comprises the main ore body and has a thickness of 3 to 40 m. Towards the middle of the dark gabbro sequence the VI ore body or magnetite seam constitutes the main ore zone, with a thickness of 30 to 60 m. Towards the upper part of the sequence the grey gabbro also contains ore seams, with thicknesses varying from 6 to 20 m. The grade of these seams is, however, rather poor (Liang et al., 1998).

Individual ore bodies or seams are strata-bound and stratiform in nature. Ore minerals are mainly composed of V-Ti-bearing magnetite, spinel, pyrrhotite, pyrite, chalcopyrite, arsenopyrite and pentlandite, with minor PGE-bearing minerals, including sperrylite (PtAs_2), erlichmanite $(\text{U,Os})\text{S}_2$, osmiridium (IrOs) , native platinum (Pt), merenskyite-moncheite $(\text{Pd,Pt})\text{Te}_2$. The PGE minerals occur mainly in V-Ti-magnetite ore zones and are associated with Co-Ni-Cu bearing sulphides, which usually contain 0.5 to 2% of the ores. More than 90% of the sulphides are comprised of pyrrhotite and chalcopyrite (Liang et al., 1998). The PGE mineralization is related to the sulphides and occurs mainly near the base of peridotite layers. PGE contents vary between 6.2 and 19.8 ppm in concentrated Co-Ni sulphides and between 0.064 and 0.877 ppm in concentrated sulphides (Liang et al., 1998).

Ore mineralogy and geochemistry carried out on the Panzhihua body suggests that PGE-bearing V-Ti-magnetite layers were formed under high oxygen fugacities (f_{O_2} : 10^{-4} to 10^{-6}) by early crystallization of magmatic melts and occur near the base of the intrusion. PGE-bearing sulphides were formed by secondary sulphide melt differentiation in silicate melts due to decreasing pressure and increasing oxygen fugacity (Liang et al., 1998).

Xinjie V-Ti-Fe-PGE deposit

The Xinjie layered intrusion is located in the southern portion of the Pan-Xi area, about 50 km northeast of Panzhihua and 5 km north of Miyi. The intrusion is characterized by igneous layering and is composed of three cumulate cycles. Cycle I consists of peridotite-pyroxenite-northeast of Panzhihua and 5 km north of Miyi. The intrusion is characterized by igneous layering and is composed of three cumulate cycles. Cycle I consists of peridotite-pyroxenite-gabbro; Cycle II comprises Fe-bearing gabbro-pyroxenite-peridotite and quartz-bearing gabbro; and Cycle III, from the base upwards, consists of plagioclase pyroxenite and quartz diorite (Liu et al., 1985). Five lithological zones (i.e., I: peridotite, plagioclase peridotite; II: plagioclase peridotite, plagioclase pyroxenite; III: gabbro, olivine gabbro; IV: olivine pyroxenite, plagioclase pyroxenite, diabase gabbro; and V: pyroxenite, plagioclase pyroxenite from base to the top) have been recognized (Zhang et al., 1997). Rock types of the Xinjie intrusion are mainly coarse-grained cumulus melagabbros, clinopyroxene-peridotites and clinopyroxenites, in which PGE, Cu and Ni mineralization has recently been recognized.



Figure 4: (a) View, looking NW, of the Xinjie intrusion; and (b) gabbro cropping out in the SE portion of the intrusion on a road to Changpo hill.

The intrusion strikes NW-SE over a distance of 7 km and is 1 km wide (Fig. 4a), with an area of about 7.5 km². Drilling has revealed grey peridotite and gabbro containing disseminated pyrrhotite and chalcopyrite. In the SE portion of the intrusion, gabbro and magnetite layers crop out on the road to Changpo hill (Fig. 4b). In this area the hanging wall rocks are Permian, Emeishan basalt, which also constitutes the footwall. The intrusion has been dated at 262 ± 2 to 278 ± 2 Ma (whole rock Sm-Nd - Fu, 2001) and at ~ 258 Ma (zircon U-Pb; unpublished data cited by Fu, 2001).

The PGE mineralization is mainly concentrated at the base of Cycle I, and is associated with Cu-Ni sulphides and Cr. The PGE-enriched layers occur in plagioclase-bearing clinopyroxenite and peridotite and are closely associated with the sulphides. The PGE-bearing V-Ti-magnetite layers consist mainly of ilmenite, high-Fe chromite and Ti-bearing, high-Fe chromite and minor Cu, Ni, Co sulphides and PGMs. The average concentrations of various metals are as follows: Fe 16.2-33.4%, TiO₂ 1.85-4.70%, V₂O₅ 0.03-0.18%, Cr₂O₃ 0.76-0.83%, Cu 0.08-0.46%, Ni 0.08-0.17%, PGE 0.241-0.630 ppm (Liang et al., 1998). The distribution of PGEs is controlled not only by the rock types, but also by the cumulate cycles. The PGE-enriched zone in the lower part of the Xinjie intrusion is the most important layer. It is 5-8 m thick with PGE contents varying from 0.30 to 1.804 ppm. The PGE concentration in the middle part of the intrusion varies from 0.20-0.42 ppm. The PGE is enriched in areas of higher Cu and Ni concentrations and where chalcopyrite, pyrrhotite, pyrite, millerite, sigenite and nickelite are present. The PGMs in the sulphides include sperrylite (PtAs₂), erlichmanite (U,Os)S₂, laurite-erlichmanite (Ru,Os)S₂ and native platinum (Pt).

Based on lithologies and PGE geochemistry, it is suggested that the Xinjie layered intrusion formed by multi-cyclic magmatic pulses, differentiation and diffusion. It is envisaged that the PGE mineralization resulted from a process of magma mixing (U- and A-type magmas; Fu, 2001) and double diffusion (Zhong, 2001). Magmatic crystallization is believed to have taken place in a closed or near closed system (Zhong, 2001).

Yangliuping Cu-Ni-PGE deposit

The Yangliuping deposit is one of the most important PGE deposits in China, with PGE metal reserves of more than 30 t. The Yangliuping deposit, which also contains significant Cu-Ni mineralization occurs in the Danba area some 30 km south of the city Danba. The deposit is situated on the eastern edge of the Qinghai-Xizang-West Yunnan fold belt in the northern portion of the Kangding fold axis. The intrusion, which is stratabound, was emplaced sill-like into the Carboniferous Daxue Group. The wall rocks, comprising quartz-sericite schist, slate, marble and quartzite, were thermally metamorphosed by the intrusion. The mineral district has nine intrusions, three of which are well mineralized. These are the Yangliuping, Zhengziyanwo and Taiziping intrusions, which are composed of peridotite, lherzolite, wehrlite, pyroxenite, gabbro (Fig. 5a) and diorite from the base upwards. The rocks are strongly altered, the ultramafic rocks in the lower part of the intrusion having been serpentinized, uralitized and steatized, while rocks in the upper part are saussuritized, sericitized and uralitized.

The ores are hosted in peridotite and lherzolite, which are strongly serpentinized, steatized and uralitized. PGE-bearing ore bodies occur in the lower part of the altered intrusion as



Figure 5: Photographs showing (a) gabbro and (b) massive pyrrhotite-chalcopyrite ores in calc silicate from the Yanliuping mine.

stratabound lenses or seams with a maximum strike length of 1300 m and a maximum width of 250 m. In addition, detached Cu-Ni-PGE mineralization has also been found within limestone and shale, but not within magmatic rocks (Fig. 5b). The ore bodies are considered to have been formed by magmatic-hydrothermal replacement (Wang et al., 2000). The ores are mainly disseminated, mottled and massive. Ore minerals include pyrrhotite, pentlandite (violarite), chalcopyrite, amoibite, cubanite, mackinawite, and pyrite. Pyrrhotite is the dominant sulphide mineral in all the ores examined. The major PGE minerals are sperrylite (PtAs_2) and borovskite (PdSbTe), which occur as euhedral crystals along the margins of violarite crystals or within pyrrhotite, pentlandite, chalcopyrite and pyrite in the massive and disseminated ores. Other PGE minerals include merenskyite (PdTe_2), michenerite (PdBiTe) and omeiite (OsAs). Gangue minerals are represented by serpentine, talc, uralite, hornblende, pyroxene, sericite, chlorite, epidote, quartz, calcite and muscovite.

The m/f ratios of the ultramafic rocks fall into the range 2.6 to 4.9 and those of mafic rocks between 0.9 and 1.7. The enrichment of metal sulphides and PGE minerals is positively related to the m/f ratios. The average concentration of Ni and Cu in densely disseminated mineralization is 1.18% and 0.38%, respectively. Average Pt and Pd concentrations of mineralized intersections are 0.104 to 0.65ppm at Yanliuping, and 0.216 to 0.405ppm at Zhengziyanwo. Average concentrations of Pt, Pd, Os, Ir, Ru and Rh from zones of massive sulphides are 1.50, 2.51, 0.435, 0.289, 0.21 and 0.24ppm, respectively. The highest PGE concentration of the hydrothermal ores at the base of the intrusion is 1.043 - 1.95ppm (Liang et al., 1998).

The PGE mineralization in the Yangliuping area is thought to have been formed by magmatic differentiation within the altered intrusion and by post-magmatic hydrothermal processes in the wall rocks along the contact zone of the intrusion (Liang et al., 1998; Wang et al., 2000).

Lufangqing PGE-bearing mafic intrusion

The Lufangqing PGE-bearing mafic intrusion is located at the Lufangqing village, about 2 km south of Panzhihua. The intrusion strikes almost N-S and is about 1000m wide and 1500 m



Figure 6: Photographs showing (a) weathered gabbro and (b) an old adit at the Lufangqing prospect.

long. It was considered to be the southern extension of the Panzhihua mafic intrusion, displaced by faulting. The Lufangqing mafic intrusion is, however, not comparable with the Panzhihua intrusion with regard to geology, lithogeochemical features and mineralization. The age of the Lufangqing intrusion is probably also different to that of the Panzhihua intrusion, but at present there is no available isotopic dating on the Lufangqing intrusion.

The Lufangqing pluton intruded the Precambrian amphibolite schists and metagabbros as well as the marble (Kangding Group) in the east and the upper Triassic conglomerates, sandstones and shales belonging to the Daqiaodi Formation in the west. The Lufangqing intrusion consists of peridotite, gabbro and pyroxenite (Fig. 6a). The occurrence was mined for copper as early as the Qing Dynasty and old adits are to be found on the Lufangqing hill (Fig. 6b), where gabbro and calc-silicate rocks outcrop.

Reconnaissance field investigations of the intrusion, undertaken by the Chinese members of the geological team, outlined a zone of Cu-Ni-PGE mineralization. The PGE-bearing ore bodies occur along the contact zones between the mafic intrusion and the marble in the east (Orebody I) and in the west (Orebody II). The mineralized zones are approximately 1500m long and 2-9 m wide in the east and about 50 m long and 2-4 m wide in the west. Ore minerals comprise sulphides (chalcopyrite, bornite, pyrrhotite, pyrite) in the altered intrusion and in the footwall marble. Concentrations of 0.55-0.90% Cu, up to 1.73% Ni and 0.1-1.73 ppm PGEs, respectively, were recorded from trench samples from Orebody I. The alteration zone is characterized by silicification and serpernitization. PGE exploration is currently being undertaken and will focus on drilling and the evaluation of potential ore bodies.

Badong PGE-bearing intrusion

The Badong PGE-bearing intrusion is located in the northern part of the Pan-Xi PGE metallogenic belt, about 5 km south of Dechang county. The intrusion was found to contain PGE mineralization during a reconnaissance geological investigation in 2000. The mafic body, which has undergone differentiation, was emplaced into Precambrian metamorphic rocks (Kangding Group) and is composed of peridotite, gabbro and pyroxenite. The PGE

mineralization occurs along the gabbro-pyroxenite contact as lenses, apparently controlled by faults. Ore minerals include chalcopyrite, bornite, pyrrhotite and pyrite. The PGE potential of the intrusion is currently being investigated.

Dayangzi PGE-bearing intrusion

The Dayangzi PGE-bearing intrusion is located in the southern portion of the Pan-Xi PGE belt, about 3 km north of Huili county. PGE mineralization was located during a reconnaissance geological investigation of the intrusion in 1999. The intrusion occurs along a NE-striking fault and is 500 m long and 20 m wide, and has been emplaced into Sinician marble. The intrusion is composed of gabbro, pyroxenite and peridotite. The PGE mineralization, which is associated with faulting (Fig7 a), occurs mainly within the altered marble and also within the intrusion along the contact between the marble and the intrusion. The mineralised zone in the marble is 430 m long and up to 6 m wide (average 3.8 m). Ore minerals consist of chalcopyrite, bornite and pyrrhotite. The mineralized zone is highly fractured and silicified (Fig. 7b) and contains 2.5% Cu, 0.6% Ni, 9.5 to 20 ppm Pt and 3.7 ppm Pd. The average concentration of Pt + Pd is 4.8 ppm. PGE concentrations in the intrusion are commonly lower than those in the marble. To the north of the Dayangzi intrusion, there are another two intrusions (viz., the 11km long and 10-20 m wide dyke-like Dakuangshan intrusion and the 2km long and 5-64 m wide dyke-like Qingshuihe intrusion), which occur along the same fault. These bodies are considered to represent the northern extension of the Dayangzi intrusion. A feature of the PGE mineralization in the latter two intrusions is the similarity with the Dayangzi mineralization. Mineralized zones are 600m long and 1 to 11m wide at Dakuangshan, and 1200 m long and 1 to 9 m wide at Qingshuihe. Concentrations of Cu, Ni and Pt+Pd are 0.2 to 0.67%; 0.22 to 0.64% and 0.31 to 2.87 ppm, respectively, at Dakuangshan, and 0.29 to 0.44%; 0.25 to 0.60% and 0.43 to 1.71 ppm, respectively, at

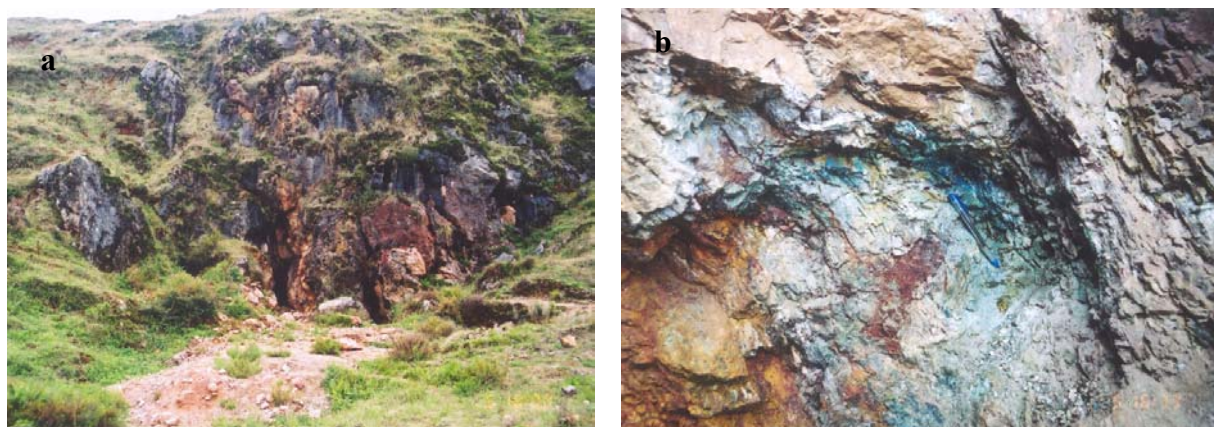


Figure 7: Photographs of the Dayanzi PGE Prospect. (a) View to the northwest of a hill of brownish-coloured, gossanous Sinician marble. The mafic intrusion (flat area in foreground) occurs near the contact with the marble, which is exposed on the hill behind the two adits seen in the centre of the photograph. (b) Sulphides in a fracture zone containing more than 12g/t PGEs at Dayanzi.

Qingshuihe. Further investigations to evaluate the PGE mineralization potential will be undertaken in the intrusions as well as in about 140 mafic dykes that have been recorded in the Dayangzi area. These dykes, which are between 300 to 1200 m long and 10 m wide, are associated with faulting that has occurred in the marble.

DISCUSSION AND COMMENTS

The geology of the Pan-Xi and Danba areas developed in three stages: (1) Precambrian (Archaean to Proterozoic) basement orogeny; (2) late Palaeozoic (late Variscan-Indosinian) rifting; and (3) Mesozoic-Cenozoic compression and fault-related depression (Pan-Xi) and intracontinental orogeny (Danba). Ultramafic-mafic intrusions in the area are mostly related, both temporally and in space, to the palaeo-rifting. The intrusive bodies, together with related acidic to alkaline intrusions and the Emeishan basalts, form a specific magmatic association, which has locally been named “one series of three igneous units”.

The ultramafic-mafic intrusions containing PGE mineralization are dominated by peridotite and gabbro. The PGE mineralization is related to magmatic differentiation and is usually enriched at the base of layered cycles in the intrusions. PGE mineralization is, however, also found in the outer contact zone between the country rock and the intrusion. This type of mineralization is possibly related to late- or post-magmatic hydrothermal processes and occurs in highly fractured and faulted country rock (mainly marble), along contact zones which are enriched in sulphides. Mineralization of this type may have resulted from the remobilisation of PGEs originally hosted in the intrusions. Hydrothermal fluids may also have played an important role in the PGE mineralization. In addition, the PGE-bearing intrusion at Danba was subjected to regional, dynamic, low-grade greenschist facies metamorphism, which led to extensive alteration.

The PGE mineralization in the ultramafic-mafic intrusions in the two areas in China, discussed in this paper, display geological and geochemical similarities as well as some differences to that found in the Bushveld Complex in South Africa. The layering and host rock types of the intrusions are similar in both regions, but the geological settings are vastly different. The Pan-Xi and Danba areas are associated with late Palaeozoic rifting, but the Bushveld Complex occurs on an Archaean-Proterozoic stable platform. In the Pan-Xi and Danba areas the PGE-bearing intrusions are of late Variscan to Indosinian age (*c.* 400-250 Ma) and are much younger than the Bushveld Complex which was emplaced in Proterozoic times (*c.* 2060 Ma). In addition, the Chinese intrusions are compositionally not as ultramafic as the Lower and Lower Critical Zones of the Bushveld Complex.

The dimensions of the PGE-bearing intrusions and tonnages of PGE ores in the Pan-Xi and Danba areas are smaller than those of the Bushveld Complex. Post-magmatic hydrothermal processes that caused PGE mineralization are also more prominent in the Pan-Xi and Danba areas compared to the Bushveld Complex. The nature of the PGE-bearing intrusions from both regions suggest that the PGE mineralization is closely related to ultramafic-mafic intrusions, irrespective of whether the intrusions were emplaced into an active or a stable geological environment. Magmatic differentiation and late- or post-magmatic hydrothermal fluids appear to be the main processes responsible for concentrating the PGE mineralization in both the Chinese and South African occurrences.

Most of the PGE-bearing intrusions in the Pan-Xi area were only found in recent years and investigated by local geological teams. The known intrusion-related PGE ore deposits and

prospects imply that this area has considerable potential for further PGE exploration. With regard to research and exploration for PGE mineralization in China, several aspects are important:

- (1) Geological events, including tectonic evolution, sedimentary sequences, magmatic intrusion, volcanic eruption, metamorphic grade and ore formation, need to be studied in detail to reconstruct the evolution and regional setting of the mineralization. A knowledge of this evolutionary development will assist in a better choice of exploration target;
- (2) A detailed study of the basement and cover rocks is needed to document their geological, lithological, geochemical and geochronological features. This includes an understanding of the magmatic processes involved with the emplacement of the ultramafic-mafic intrusions, including their crystallization history, magmatic differentiation and chemical contamination of magmas;
- (3) The Chinese layered complexes, in particular, require additional petrological and geochemical study for comparative purposes and in order to determine possible target areas for the presence of PGE and other mineralization types;
- (4) Hidden or poorly exposed PGE-bearing ultramafic-mafic intrusions, for example in the Danyanzi region, need to be investigated using aeromagnetic and gravity surveys as well as geochemical exploration techniques; and
- (5) There is a need to integrate geological, geochemical and geophysical data throughout the region where the ultramafic-mafic intrusions occur – the emphasis being to evaluate the mineralization potential of these igneous bodies.

CONCLUSIONS

Ultramafic-mafic intrusions containing PGE mineralization in the Pan-Xi and Danba areas of the Sichuan Province in southwest China are located along the central and northern parts of the Archaean-Proterozoic Kangding Axis adjacent to the western margin of the Yangtze Platform. The intrusions are thought to be late Palaeozoic (e.g. Variscan-Indosinian: 400 to 250 Ma) in age, during which time the regional geotectonics gave rise to a rift environment. The intrusions coexist in time and space with acidic-alkaline granitoids and basalts, suggesting that the igneous bodies were formed from the same or contemporaneous magma sources.

The Panzhiuha and Xinjie intrusions are characterized from the base upwards, with layers consisting of peridotites, pyroxenites and plagioclase-bearing gabbroic rocks. The other intrusions in the region mainly consist of pyroxenites and gabbros without obvious layering. The PGE mineralization occurs near the base of individual magmatic cycles and is enriched in sulphides, the latter particularly being related to late- or post-magmatic hydrothermal fluids.

The various PGE mineralization types include the following: (1) magmatically layered Cu-Ni-PGE (Xinjie); (2) hydrothermally altered Cu-Ni-PGE (Badong, Dayanzi, Lufangqing); and (3) magmatic-hydrothermal Cu-Ni-PGE (Yangliuping). The ore minerals are dominated by chalcopyrite, pyrrhotite and pyrite in types 2 and 3. PGE minerals are mainly composed of sperrylite (PtAs_2), borovskite (PdSbTe), merenskyite-moncheite (Pd,PtTe_2), erlichmanite

(OsS₂), laurite-erlichmanite (Ru,Os)₂S₂, osmiridium (IrOs) and native platinum (Pt). The type 2 and 3 intrusions, and their contact zones with country rocks, are mostly altered by silicification, sulphidization, serpentization and carbonatization. The country rock contact zone at Dayanzi is highly fractured, silicified and sulphidized and contains high PGE contents of up to 16 ppm. It is suggested, on the basis of field observations, that the PGE mineralization in the two areas resulted from magmatic differentiation (type 1) and by late or post-magmatic hydrothermal processes (types 2-3).

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