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山西省垣曲县幅 1∶50 000 地质图数据库

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摘要：山西省垣曲县幅 (I49E005015)1∶50 000 地质图数据库是根据中国地质调查局地质调查工作和地质行业的统一标准及要求，在充分利用该区 1∶200 000、1∶250 000 等区域地质矿产调查成果资料的基础上，通过采用数字填图系统进行野外地质填图形成的。野外共采集岩石化学分析样品 54 件，同位素测年样品 7 件。通过本数据库的建立，对中条山地区“涑水杂岩”进行了解体，查明了该区变质基底的物质组成及构造轮廓；对古元古界进行了重新厘定划分，提出中条山地区古元古界新的划分方案；对中元古界熊耳群进行了“火山构造–岩性岩相–火山地层”三重填图及同位素测年，限定了该区中元古界的底界年龄；系统总结了该区变质岩建造特征；提出中条山地区古元古代 3 期构造叠加样式，对中条山核心铜矿区胡–篦型铜矿的成矿规律、构造控矿的研究有重要指导意义。

关键词：数据库；地质图；地质调查工程；1∶50 000；垣曲县幅；山西省

数据服务系统网址：http://dcc.cgs.gov.cn

1 引言

山西省垣曲幅位于中条山北段（图 1），中条山区地处华北地块南缘，其东衔华北东部地块，西邻鄂尔多斯地块，南靠秦岭造山带，大地构造位置独特。在前寒武纪构造格架划分方案中，属华北地块中部造山带的范畴（赵国春等, 2002）。中条山地区前寒武纪地质研究对探讨华北地块前寒武纪构造格局和构造演化具有重要意义（赵风清, 2006）。

中条山变质基底主要由“涑水杂岩”与古元古界组成，“涑水杂岩”为中条地块最古老的地质单元，根据对其不同岩性单元的锆石 U–Pb 年代学研究认为“涑水杂岩”中虽有部分太古宙岩石存在，但其主体岩浆活动发生在古元古代（孙大中和胡维兴, 1993）。而根据区域地质分析认为“涑水杂岩”应为太古代大陆岩浆弧作用的产物（白

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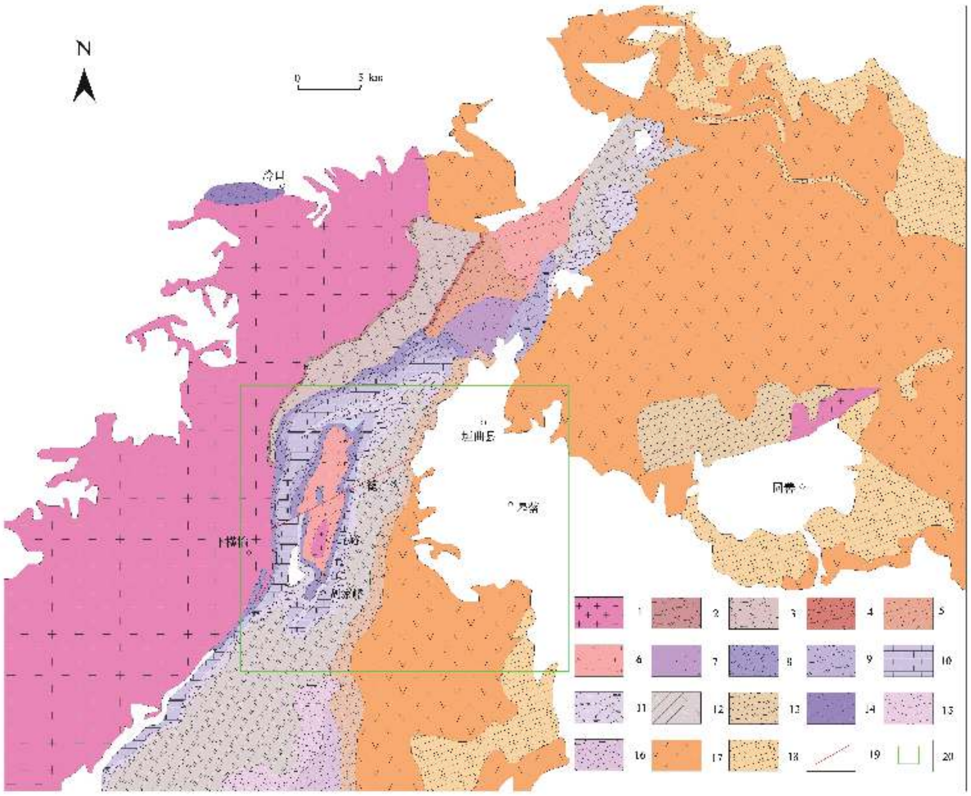

图 1　中条山北段地质图（据赵凤清等, 2006 修改）

1—新太古代—古元古代涑水杂岩；2—古元古代冷口岩组；3—古元古代平头岭组；4—古元古代铜凹组；5—古元古代后山村组；6—古元古代园头山组；7—古元古代竖井沟组+西井沟组；8—古元古代骆驼峰组；9—古元古代界牌梁组；10—古元古代龙峪组；11—古元古代余元下组；12—古元古代篦子沟组；13—古元古代余家山组；14—古元古代温峪组；15—古元古代吴家坪组；16—古元古代宋家山群；17—中元古代熊耳群；18—中元古代汝阳群；19—断层；20—垣曲县幅位置

瑾等, 1997）。对山西省垣曲地区北峪花岗岩的岩石地球化学、同位素年代学进行了详细研究，提出绛县地区“涑水杂岩”主体形成于古元古代（赵凤清和唐敏, 1994 ; 赵凤清, 1997）。在中条山“涑水杂岩”中识别出 2 期新太古代 TTG 岩石，推测中条山区在新太古代有 2 期大陆地壳生长事件（张瑞英等, 2012, 2013, 2015）。

中条山区出露有较为齐全的古元古代变质地层，夹有大量变质火山岩地层，其特点在华北地块其他地区极为少见，为开展年代地层研究提供了理想的研究对象（赵凤清等, 2006）。中条山古元古界包括冷口变质火山岩、绛县群、中条群及担山石群，已为多数学者所认同（杨崇辉等, 2018）。近年来，所获得一系列研究成果表明，该区存在广泛的古元古代裂谷背景下的沉积–火山活动。中条山保存有古元古代重大地质事件造就的构造界面，构造–热事件十分发育，是研究古元古代岩石圈结构和演化十分理想的地区。

山西省垣曲幅位于中条山成矿区的核心部位，成矿地质条件优越。该区地质矿产调查始于 20 世纪 20 年代，前人先后进行过不同性质、不同程度矿产调查、专题研究和不同比例尺的区域地质调查及物化探工作，对该地区的沉积火山岩建造、变质岩石特征、变质构造、年代学等方面进行了大量研究（孙大中等, 1991; 孙继源等, 1995; 白瑾, 1993;白瑾等, 1997; 赵凤清等, 2006），也取得了较丰富的地质矿产资料，这些前期工作

为本次 1∶50 000 区域地质调查工作的开展奠定了基础。近年来，随着一些新的地质理论、技术方法的引进和提高，在五台—恒山—吕梁地区取得了突破性成果及认识。中条山区作为华北地块早前寒武纪经典地区在变质基底及成矿作用研究方面存在众多关键地质问题，其突出的问题有："涑水杂岩"的物质组成、形成时代；古元古代地层系统的重新认识、厘定与划分；重要构造界面性质的界定、构造背景、时代、含矿性等；中—新元古界划分方案、区域对比研究、重要界面性质、形成时限确认、熊耳群火山构造与铜矿的关系；中条山构造格架研究；中条山年代格架建立；等等。此外，随着近年来中条山铜矿区开采力度的不断加大，主要矿区面临资源枯竭，因而需对中条山不同类型铜矿的成矿地质背景进行深入研究。在此背景下，中国地质调查局围绕"中条山黄金地段"作为示范区，围绕金、铜、钼等重点矿种，以该区复杂的早前寒武纪地质背景为重点开展 1∶50 000 精细地质调查评价工作，从而支撑找矿突破战略行动、破解中条山重大地球科学技术难题，服务经济社会发展的重大需求。

山西省垣曲县幅 1∶50 000 地质图及数据库（表 1，孙华等，2020）是中国地质调查局天津地质调查中心承担的中条–熊耳山成矿区地质矿产调查项目的成果资料之一。

表 1　数据库（集）元数据简表

条目	描述
数据库（集）名称	山西省垣曲县幅1∶50 000地质图数据库
数据库（集）作者	沉积岩类：孙　华 山西省地质调查院 火山岩类：侯冬红 山西省地质调查院 岩浆岩类：刘伟东 山西省地质调查院 变质岩类：赵建新 山西省地质勘查局214地质队 地质构造：李建荣 山西省地质调查院
数据时间范围	2016—2018年
地理区域	经纬度：东经111°30′~111°45′，北纬35°10′~35°20′
数据格式	MapGIS
数据量	69.2 MB
数据服务系统网址	http://dcc.cgs.gov.cn
基金项目	中国地质调查局地质调查项目"山西1∶50 000绛县幅、垣曲县幅、同善镇幅区域地质矿产调查"（项目编号：DD20160043-01）资助
语种	中文
数据库（集）组成	垣曲县幅1∶50 000地质图数据库包括:1∶50 000地质图库和图饰。地质图库包括沉积岩、岩浆岩、火山岩、变质岩、第四系、脉岩、构造、地质界线、产状、岩性花纹、各类代号等。图饰包括接图表、柱状图、图例、图切剖面、侵入岩简表、责任表等

2　数据采集和处理方法

2.1　数据基础

山西省垣曲县幅 1∶50 000 地质图是以《区域地质调查技术要求（1∶50 000）》（DD 2019-02）为指导，以《数字地质图空间数据库标准》（DD 2006-06）为数据库建库依据编制而成。垣曲县幅的数字线划地图（Digital Line Graphic，缩写 DLG）数据由国家测绘局提供，地形线数据来源于山西省地理信息局提供的 DWG 格式数据。应用已有的技术标准和数字填图系统（DGSS）、MapGIS 等计算机软件进行数据处理。

2.2 数据处理过程

本图幅投影系统为高斯-克吕格投影参数，坐标系统为西安 80。在野外数字填图掌上电脑中以 1∶25 000 地形图为底图，通过野外实际路线调查，在数字填图系统中标绘出地质点、界线点和地质界线及路线等点、线信息，观察并录入各点、线的性质、岩性、产状等信息，初步建立数字填图（PRB）数据库。将野外采集的地质点 PRB 数据资料全部导入电脑中，并根据相应规范进行数据整理和辅图编制，完成垣曲县幅数字地质图编制。以本次野外实际采集的 PRB 数据绘制实际材料图，在此基础上对地层单元界线、建造花纹、反映各类建造的构造形态进行绘制，对新形成的地质单元的界线进行勾连，编制建造–构造图（图 2）。

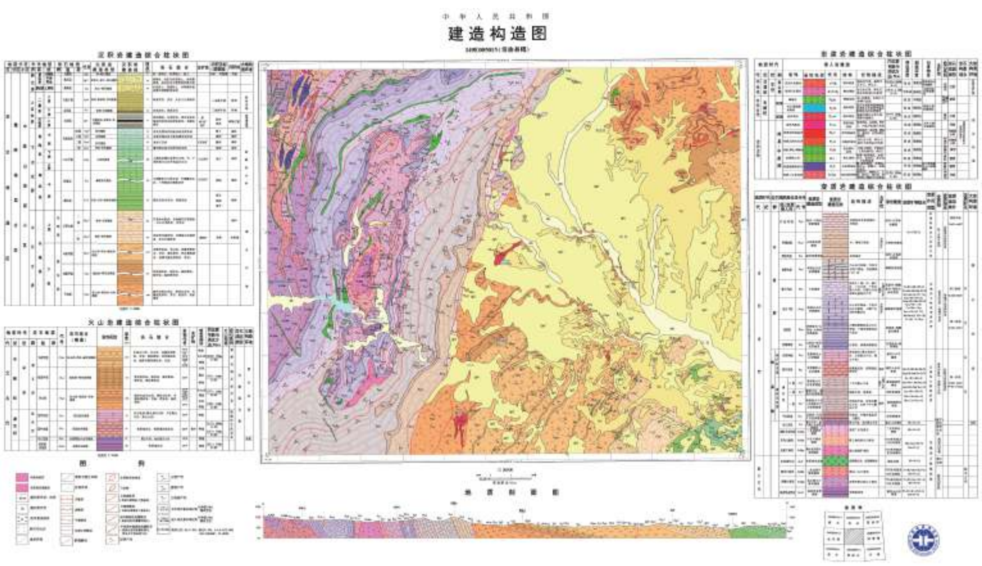

图 2　山西省垣曲县幅（I49E005015）1∶50 000 建造构造图

3　数据样本描述

3.1　数据的命名方式

地质面.wp，地质线.wl，地质点.wt。

3.2　图层内容

主图内容包括沉积岩建造、火山岩建造、侵入岩建造、变质岩建造、第四系、构造、地质界线、产状、各类代号等。

图饰内容包括接图表、柱状图、图例、图切剖面、责任表等。

3.3　数据类型

实体类型名称：点、线、面。

点实体：各类地质体符号及标记、地质花纹。

线实体：断裂构造、地质界线、岩相界线等。

面实体：沉积岩、火山岩、变质岩、侵入岩、第四系等。

3.4　数据属性

山西省垣曲县幅（I49E005015）1∶50 000 矿产地质图数据库包含地质实体要素信息、地理要素信息和地质图整饰要素信息。地理要素信息属性沿用国家测绘地理信息局

收集数据的属性结构。地质实体要素信息属性按照 1：50 000 区域地质调查地质填图数据库建库要求分四大岩类（沉积岩、火山岩、侵入岩、变质岩）、断裂构造、产状要素等分别建立数据库属性。

沉积岩建造数据属性主要有：年代地层单位、岩石地层单位、建造名称、建造代码、岩性组合、地层时代、建造厚度、建造含矿性、岩石结构、沉积构造、岩石颜色、沉积作用类型、沉积相类型、同沉积构造。

火山岩建造数据属性主要有：年代地层单位、岩石地层单位、建造名称、建造代码、地层时代、地层分区、岩性组合、建造厚度、建造含矿性、火山喷发旋回、火山喷发类型、火山岩成因类型、特殊岩性夹层、火山岩相类型、同位素年龄。

侵入岩建造数据属性主要有：建造名称、建造代码、岩性组合、建造含矿性、岩石结构、岩石构造、侵入期次、岩体产状、平面形态、剖面形态、岩体侵位构造特征、接触带特征、成因类型、同位素年龄。

变质岩建造数据属性主要有：年代地层单位、岩石地层单位、建造名称、建造代码、岩性组合、地层时代、建造厚度、建造含矿性、岩石结构、岩石构造、原岩建造、变质相、变质作用类型。

断裂构造数据属性主要有：断裂名称、断裂类型、断裂延长、断裂延深、断裂宽度、断裂走向、断裂面倾向、断裂面倾角、断距、断裂面形态、构造岩特征、运动方式、活动期次、力学性质。

产状数据属性主要有：产状类型、倾向、倾角。

4 数据质量控制和评估

地质填图按照《矿产地质调查技术要求（1：50 000）》（DD 2019−02）执行，对地质条件复杂地区进行路线加密调查，保证把野外资料全面客观地反映到地质图之上。地质点采集以充分控制重要地质界线、构造界线、与成矿有关的地质体、矿化蚀变带等为原则。为编制山西省垣曲县幅 1：50 000 地质图，本次野外地质路线调查总长度 587.8 km，地质点 868 个，地质界线 1 169 条，平均 304 m 路线含一个地质点或点间界线；完成各比例尺剖面长度 44.9 km；完成硅酸盐微量、稀土元素分析样品各 50 件，薄片鉴定样品 174 个，人工重砂 7 件，锆石 U–Pb 年龄样品 7 件，产状 400 个，照片 216 张。

图面表达一般只表达直径大于 100 m 的闭合地质体，宽度大于 50 m、长度大于 250 m 的线状地质体，以及长度大于 250 m 的断层、褶皱构造。对矿化蚀变构造带及其他矿化地质体规模不论大小，均在图上表示；厚度较小者，用适当的花纹、符号放大或归并表示。一般地质点在野外手图上所标定的点位与实地位置误差不大于 25 m。

数据质量方面，填图路线自检、互检达 100%，项目组抽检 30%，符合地质调查项目质量管理要求。中国地质调查局天津地质调查中心组织有关专家分别于 2016 年 10 月 26—29 日和 2017 年 11 月 10—14 日对项目进行了两次野外现场质量检查，对项目运行以来的工作情况、工作进度和质量、完成的主要实物工作量、取得成果进展和内部质量管理情况等进行全面抽查，并对其质量进行评述，质量检查等级为优秀。2018 年 10 月 22—27 日，中国地质调查局天津地质调查中心组织专家采用室内、野外现场两者相结合的检查方法对垣曲县测区进行了野外验收，经验收专家综合评定，垣曲县幅（I49E005015）得分 92 分。

5 数据价值

山西省垣曲县幅（I49E005015）1：50 000 地质图是中国地质调查局开展新一轮矿产地质调查工作的示范图幅。本次工作重点对中条山多年来存在的关键地质问题进行了调查，在野外地质研究基础上，还获得了 54 件样品的地球化学数据和 7 件同位素年代学数据（表 2），强调了以同位素年代学、地球化学、变质作用等研究为手段，重点探索了五台构造事件、吕梁（中条）构造事件的时限、构造意义，突出了构造–岩浆热事件的研究。通过深入的研究和对关键问题的剖析，在“涑水杂岩”性质、时代、归属，元古界厘定划分、地质构造研究及中元古界长城系的划分、形成时代等方面取得了重要的进展。同时查明了区内变质岩原岩建造类型及特征（表 3），编制了建造–构造图，详细研究了变质作用类型及变质相，认真分析了矿物组合，合理划分了变质相带，为该地区的地质找矿工作提供了基础数据支撑，为科技创新发挥了引领作用，提升了矿产地质调查工作服务资源安全、经济社会发展和生态文明建设的能力。

表 2　山西省垣曲县幅（I49E005015）地质图空间数据库测试分析表

数据类型	数据量	数据基本特征
岩石化学分析数据	54件	火山岩、侵入岩的14种主量元素
微量元素分析数据	54件	火山岩、侵入岩的14种微量元素
稀土元素分析数据	54件	火山岩、侵入岩的15种稀土元素
同位素年龄数据	7件	火山岩、侵入岩的LA-ICP-MS锆石U-Pb同位素年龄

5.1 “涑水杂岩”新认识

将山西省垣曲县幅内“涑水杂岩”解体为新太古代及古元古代不同的地质单位，对重新认识该区的变质基底形成与演化提供了依据。

将新太古代变质岩系划分为柴家窑表壳岩、西姚片麻岩（TTG）、钙碱性解州片麻岩（CA 系列）、变质辉长岩等 4 个地质体单位。在柴家窑表壳岩（变质流纹岩）中新获得 2 511±13 Ma 的年龄信息。结合西姚片麻岩被寨子片麻岩、东沟片麻岩和横岭关变质花岗岩侵入的地质依据、年龄信息（2 553±21 Ma、2 543±21 Ma、2 551±2.7 Ma，本次工作）、岩石化学特征等资料，认为西姚片麻岩可能形成于太古代晚期（～2.7 Ga）初生地壳的部分熔融。首次在区内划分了解州片麻岩（2 530±13 Ma，本次工作），岩石化学特征反映其属于高钾钙碱性 I 型花岗岩，其可能形成于 2.5～2.8 Ga 的初生地壳部分熔融，进一步证明中条山新太古代地块形成于岛弧构造体系，推测该区存在～2.5 Ga 陆壳增生事件，即太古代末已完成克拉通化。

新发现一期 2 350～2 200 Ma 的岩浆热事件。解体划分为北峪片麻岩、东沟片麻岩、横岭关片麻岩、变质超镁铁质侵入岩、变质辉长岩等单位。在北峪变质奥长花岗岩中新获得 2 313±13 Ma 的年龄，在横岭关变质花岗岩中新获得 2 235±13 Ma 的年龄。岩石化学特征方面，东沟片麻岩、北峪片麻岩与太古代 TTG 岩石地球化学特点相似，同时与埃达克岩的地球化学特点总体相似，显示出同造山花岗岩的特点。横岭关变质花岗岩在地球化学特点上具有典型钙碱性花岗岩的特点，可能代表同造山–后造山阶段产物。

5.2 绛县群新认识

将山西省垣曲县幅内绛县群划分为横岭关亚群及铜矿峪亚群，形成时代由新太古界调整为古元古界，查明绛县群横岭关亚群与中条群为角度不整合接触，在绛县群竖井沟

表 3　山西省垣曲县幅（I49E005015）1：50 000 地质图变质岩建造一览表

代	纪	群	组/岩体	代号	变质岩建造类型	岩性描述	原岩建造	变质矿物组合	变质作用类型	变质相
古元古代	滹沱纪	担山石群	沙金河组	Pt_1sj	砾岩-石英岩变质建造	变质砾岩夹砂质板岩、石英岩	砾岩-石英砂岩建造	Ser+Chl+Q	区域低温动力变质作用	低-次绿片岩相
			西峰山组	Pt_1xf	石英岩变质建造	中、厚层石英岩	石英砂岩建造			
			周家沟组	Pt_1z	砾岩变质建造	变质砾岩	砾岩-石英砂岩建造			
		中条群	余家山组	Pt_1yj	厚层白云岩变质建造	白云石大理岩、方柱白云石大理岩，夹炭质板（片）岩	碳酸盐岩建造	St+Bit+Ms+Pl+Q St+Alm+Bit+Ms+Pl+Q	区域动力热流变质作用	低角闪岩相-低绿片岩相
			篦子沟组	Pt_1b	片岩建造	炭质片（板）岩、绢片岩、二云片岩、十字石榴云片岩、石榴云片岩，局部夹堇青石片岩	泥质岩-碳酸盐岩-基性火山岩建造	Bit+Ms+Q+Pl±Ky Alm+Bit+Ms+Q		
			余元下组	Pt_1yy	厚层白云岩变质建造	白云石大理岩、方柱白云石大理岩，上部产分支柱状叠层石	碳酸盐岩建造	Alm+Bit+Ms+Pl+Q Alm+Bi±Chl		
			龙峪组	Pt_1ly	砂质板岩-石英岩-大理岩变质建造	上部钙质板岩夹白云大理岩；下部砂质板岩夹石英岩	砂泥质-碳酸盐岩建造	Cc+Bit±Scp Ser+Ab+Q±Chl		
			界牌梁组	Pt_1j	石英岩-砾岩变质建造	石英岩，底部变质砾岩	石英砂岩-砾岩建造	Bit+Ms+Q±Pl±Chl Cc+Q±Tr+Scp		
		绛县群	西井沟组	Pt_1x	变质基性火山岩建造	变玄武岩（黑云角闪片岩、方柱黑云片岩、黑云片岩）	基性火山岩建造	Alm+St+Bit+Ky+Ms+Q	区域动力热流变质	低角闪岩相-低绿片岩相
			竖井沟组	Pt_1s	变质酸性火山岩建造	变质流纹岩、变质流纹英安岩	酸性火山岩建造	Alm+Bit+Ms+St+Q+Pl		
			铜凹组	Pt_1t^3	富铝绢云片岩变质建造	十字石榴云片岩	富铝泥质岩建造	Ky+Bit+Ms+Q Alm+Bit+ Ms（Ser）+Q		
				Pt_1t^2	绢英片岩、绢英岩变质建造	绢英片岩、绢英岩	泥砂质建造	Alm+Cht+Ms（Ser）+Q		
				Pt_1t^1	富铝绢云片岩-含碳绢云片岩变质建造	含炭绢片岩、含炭石榴云片岩、含炭十字石榴云片岩	富铝泥质岩建造	Scp+Bit+Hb+Q		
			平头岭组	Pt_1p	石英岩-云母片岩变质建造	石英岩，中部含蓝晶石、石榴石	砂泥质建造	Cht+Chl+Ser+Q Bit+Chl+Ser+Q		

续表 3

代	纪	群	组/岩体	代号	变质岩建造类型	岩性描述	原岩建造	变质矿物组合	变质作用类型	变质相
古元古代	滹沱纪		冷口岩组	$Pt_1l.$	黑云片岩、角闪黑云片岩变质建造	黑云片岩、角闪黑云片岩	基性火山岩建造	Hb+Ab+Q	区域动力热流变质	角闪岩相
			横岭关花岗岩	Pt_1Hgn	二长花岗岩建造	变质二长花岗岩	二长花岗岩建造	Hb+Ab+Q		低角闪岩相
			东沟片麻岩	Pt_1Dgn	闪长片麻岩建造	黑云角闪斜长片麻岩	TTG系列英云闪长岩建造	Hb+Alm+Pl+Q		高角闪岩相
			北峪片麻岩	Pt_1Bgn	奥长花岗质片麻岩建造	奥长花岗质片麻岩	TTG系列奥长花岗岩建造	Hb+Pl+Q		
新太古代			变质基性岩	Ar_3N	变质基性岩墙	变质辉长岩、变质辉绿岩	基性岩墙	Hb+Pl+Q		角闪岩相
			解州片麻岩	Ar_3Hgn	二长花岗片麻岩建造	黑云二长片麻岩	TTG系列花岗闪长岩建造	Pl+Kf+Bit+Sill+Q Hb+Pl+Q		高角闪岩相
			西姚片麻岩	Ar_3Xgn	英云闪长片麻岩建造	条带状黑云斜长片麻岩	TTG系列英云闪长岩建造	Pl+Kf+Bit+Sill+Q Hb+Pl+Q		
			柴家窑表壳岩	Ar_3csr	流纹岩变质建造	变质流纹岩	酸性火山岩建造	Pl+Kf+Bit+Sill+Q Hb+Pl+Q		

注：Ser—蛇纹石; Chl—绿泥石; Q—石英; St—十字石; Alm—铁铝榴石; Bit—黑云母; Ms—白云母; Tr—透闪石; Pl—斜长石; Ky—蓝晶石; Cht—硬绿泥石; Cc—方解石; Scp—方柱石; Hb—普通角闪石; Ab—钠长石; Kf—钾长石; Sill—矽线石。

组火山岩中新获得 2 137±16 Ma 及 2 147±13 Ma 的年龄值，准确限定了绛县群的沉积底界，为研究滹沱裂谷盆地的沉积背景及时限提供了数据支撑。

5.3　熊耳群新认识

将山西省垣曲县幅内中元古代熊耳群重新进行了划分，首次在中条山区填绘了鸡蛋坪组，查明了熊耳群的顶底接触关系，新获得了一批年代学数据，限定了区内熊耳群火山活动的时限，为解决“吕梁运动”的性质及区域构造意义提供了依据。

本次在侵入于许山组的潜流纹岩中新获得 1 788±14 Ma（东周家凹）、1 777±15 Ma（楼子庄）的年龄值；在鸡蛋坪组酸性火山岩（熔岩）中新获得 1 777±14 Ma（贾宝山）的年龄值。

5.4　新识别大型伸展剥离构造及变质核杂岩

在山西省垣曲县幅识别出一期古元古代大型伸展剥离构造及变质核杂岩，该期构造控制了整个中条山区滹沱系（包括绛县群、中条群）的空间展布及胡–篦型铜矿的形成规律，该期构造受古元古代主期构造的影响，空间形态具有复杂的构造样式，在不同构造区呈现不同的构造形式，总体可概括为北峪变质核杂岩构造、“涑水杂岩”与上覆绛县群（中条群）之间的伸展型韧性剪切带、“上玉坡短轴背斜”区剥离构造体系等。

5.4.1　限定主剪切带形成时代为古元古代早期

查明绛县群、中条群底部层位与下伏基底片麻岩间呈明显的韧性断裂接触，地层出现了严重缺失现象，下盘岩石已被强烈改造成糜棱片岩、糜棱片麻岩，块状岩石完全片理化，形成比较典型的糜棱岩和构造片岩系列。而上盘绛县群、中条群内部则普遍形成以褶叠层系统为代表的顺层掩卧褶皱群落、顺层片理化带等。大量的剪切运动标志体表明，主剪切带的剪切运动方向为上盘（SE 盘）由 NW 向 SE 正向滑移。本次在主剪切带附近横岭关岩体中获得的年龄值为 2 231±86 Ma，而在绛县群铜矿峪亚群变质火山岩中获得 2 137±16 Ma 与 2 147±13 Ma 的年龄值，在侵入于绛县群铜凹组的烟庄二长花岗岩中新获得 2 128±14 Ma 的年龄信息，限定了主剪切带形成时代为古元古代早期的伸展阶段。

5.4.2　确认北峪变质核杂岩构造及边界断裂特征

北峪变质核杂岩构造主体由北峪片麻岩体（核）和剥离断层组成，北峪片麻岩体呈穹状隆起，岩石塑性变形强烈，流状构造及片理很明显，带内岩石为典型的糜棱岩或超糜棱岩（野外似构造片岩），形成时代为古元古代（本次新获得 2 313±13 Ma 的年龄）。剥离断裂产出于北峪片麻岩体与绛县群之间，绛县群缺失下部层位，变形强烈，但表现为脆韧性变形，变形习性的差异记录了变质基底的长期隆升过程。据两盘香肠构造、S–C 组构、小褶皱等特征分析，剪切带是在左旋剪切机制下形成的，为东盘（上盘）下滑、西盘（下盘）上升的正断层式活动机制。

5.4.3　查明“上玉坡短轴背斜”区剥离构造体系为三层结构模式

在垣曲县幅内，“上玉坡短轴背斜”呈现复杂的构造轮廓，主要由该期区域性剥离断层经晚期褶皱叠加造成。主断裂系统实为继承了中条群不同岩性差异面而发展起来的多级别大型韧性剥离断层系统，由主断裂及数条分支断裂复合组成。主要的断裂有 3 条，中条群底部的断层为主剥离断层，篦子沟组上下界面的断裂为支剥离断层，共同组成剥离断层系统。平面上呈平行排列，剖面上排除褶皱影响后构成三层结构模式（图 3）。

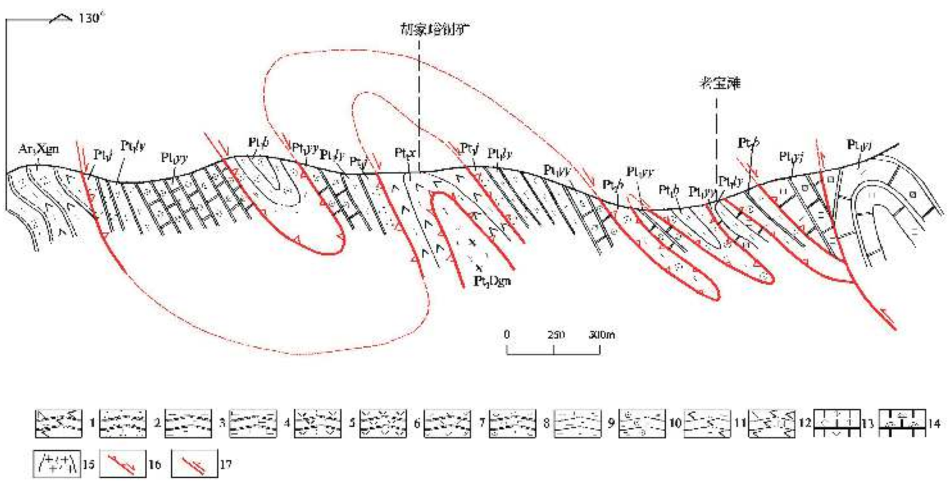

图 3　垣曲县胡家峪铜矿—老宝滩地质构造剖面
1—黑云角闪斜长片麻岩；2—石英岩；3—钙绢片岩；4—钙质板岩；5—变流纹凝灰岩；6—变质流纹岩；7—变质英安岩；8—变质砾岩；9—钙质二云片岩；10—含榴二云片岩；11—黑云角闪片岩；12—斜长角闪（片）岩；13—白云石大理岩；14—叠层石大理岩；15—片麻状花岗岩；16—中条山基底剥离断层；17—逆断层

5.5　地理底图与数据库新成果

以新的 1∶50 000 数字化地理底图、数据库为基础，统一采用 1980 西安坐标系统，充分吸收、补充近年来的最新地理资料，编制了精度高、资料新的垣曲县幅地理底图，并建立了空间数据库。提交了 4 幅 1∶25 000 图幅 PRB 库、实际材料图数据库和垣曲县幅 1∶50 000 地质图成果空间数据库，各类数据齐全，表达方式符合规范（李洪英等, 2018），达到数据库建设的技术要求，为进一步加强区域公益性地质资料的社会化服务提供了数据支撑。

6　结论

（1）山西省垣曲县幅（I49E005015）1∶50 000 地质图是中国地质调查局在中条山核心成矿区部署的地质矿产调查的示范图幅，项目组以解决中条山重大地质问题为工作目的开展了新一轮地质填图，突出了变质地质及构造成果的表达，该图幅对中条山基础地质背景研究、矿产地质研究有重要的指导意义。

（2）对中条山地区“涑水杂岩”进行了解体，基本查明了该区变质基底的物质组成；对古元古界进行了重新厘定与划分，提出中条山区古元古界新的划分方案；对中元古界熊耳群进行了“三重”填图及同位素测年，限定了该区中元古界底界；系统总结了该区变质岩建造特征；提出中条山古元古代 3 期构造叠加样式。新的成果资料对重新认识中条山地层构造格架有重要价值。

（3）全面编制了 1∶50 000 垣曲县幅地质图并建立了空间数据库，提交了 4 幅 1∶25 000 图幅 PRB 库、实际材料图数据库，各类数据齐全，表达方式符合规范，达到数据库建设的技术要求，为加强区域公益性地质资料的社会化服务提供了数据支撑。

致谢：山西省垣曲县幅 1∶50 000 地质图是一项集体成果，野外一线地质工作人员付出了辛勤的努力。在项目实施过程中，得到多位地质专家的辛勤指导，特别是中国地质调查局天津地质调查中心二级项目组骨干人员李承东、赵利刚、曾威、许腾对本项目正常开展、地质成果的提升起到决定性的作用。在此对各位专家和野外项目组所有成员表示最诚挚的感谢。

参考文献

白瑾, 余致信, 颜耀阳, 戴风岩. 1997. 中条山前寒武纪地质 [M]. 天津: 天津科学技术出版社.

白瑾. 1993. 华北陆台北缘前寒武纪地质及铅锌成矿作用 [M]. 北京: 地质出版社.

李洪英, 叶会寿, 杨磊, 耿艳光, 毕珉烽, 尹德威, 薛生升, 简伟, 范成龙, 王梦琦, 赵楠. 2018. 山西中条山地区前寒武纪铜矿专题填图实践与思考 [J]. 地质通报, 37(2–3): 271−282.

孙大中, 胡维兴. 1993. 中条山前寒武纪年代学构造格架和年代地壳结构 [M]. 北京: 地质出版社.

孙大中, 李惠民, 林源贤, 周慧芳, 赵风清, 唐敏. 1991. 中条山前寒武纪年代学、年代构造格架和年代地壳结构模式的研究 [J]. 地质学报, 65(3): 216–231.

孙继源, 冀树楷, 真允庆. 1995. 中条裂谷铜矿床 [M]. 北京: 地质出版社.

孙华, 侯冬红, 刘伟东, 赵建新, 李建荣. 2020. 山西省垣曲县幅 1：50 000 地质图数据库 [DB/OL].地质科学数据出版系统. (2020-06-30). DOI: 10.35080/data.A.2020.P13.

杨崇辉, 杜利林, 宋会侠, 任留东, 苗培森, 路增龙. 2018. 华北克拉通古元古代地层划分与对比 [J]. 岩石学报, 34(4): 1019−1057.

赵国春, 孙敏, Wilde SA. 2002. 华北克拉通基地构造单元特征及早元古代拼合 [J]. 中国科学, 32(7): 538−549.

赵风清. 2006. 山西中条山地区古元古代地壳演化的年代学和地球化学制约 [D]. 北京: 中国地质大学 (北京) 博士论文.

赵风清, 唐敏. 1994. 晋南中条山北峪奥长花岗岩的岩石地球化学 [J]. 华北地质矿产杂志, 9(3): 271−280.

赵风清. 1997. 中条山地区北峪奥长花岗岩的同位素年龄和同位素地球化学特征 [J]. 前寒武纪研究进展, 20(1): 44−50.

赵风清, 李惠民, 左义成, 薛克勤. 2006. 晋南中条山古元古代花岗岩的锆石 U-Pb 年龄 [J]. 地质通报, 25(4): 442−447.

张瑞英, 张成立, 第五春荣, 孙勇. 2012. 中条山前寒武纪花岗岩地球化学、年代学及其地质意义 [J]. 岩石学报, 28(11): 3559−3573.

张瑞英, 张成立, 孙勇. 2013. 华北克拉通 ~ 2.5 Ga 地壳再造事: 来自中条山 TTG 质片麻岩的证据 [J]. 岩石学报, 29(7): 588−597.

张瑞英. 2015. 华北克拉通南部中条山地区涑水杂岩的组成与演化 [D]. 西安: 西北大学博士论文.

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1∶50 000 Geological Map Database of Yuanqu Map-sheet, Shanxi Province

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Abstract: The 1∶50 000 geological map database of Yuanqu map-sheet (I49E005015), Shanxi Province was developed in accordance with the standards and requirements of geological surveys proposed by the China Geological Survey and the unified standards and requirements applicable to the geological industry, for which the achievements obtained from previous 1∶200 000 and 1∶250 000-scale regional geological surveys were fully utilized. Meanwhile, the Digital Geological Survey System (DGSS) was adopted for geological field mapping. A total of 54 samples for petrochemical analysis and seven samples for isotope dating were collected in the field. The following achievements were obtained by establishing the Database. The material composition of the metamorphic basement in Zhongtiao Mountain area and the tectonic framework of the area were ascertained by breaking up the Sushui complex in the area. The Paleoproterozoic boundary of Zhongtiao Mountain was redetermined and a new division scheme of the boundary was put forward. The volcanic structures, lithology and lithofacies, and volcanic strata of the Mesoproterozoic Xiong’er Group were mapped, and isotopic dating was conducted for the group. As a result, the age of Mesoproterozoic lower boundary of Zhongtiao Mountain was restricted. Furthermore, the characteristics of metamorphic rock formations were systematically summarized, and three stages of tectonic superimposition patterns of the Paleoproterozoic in Zhongtiao Mountain were proposed. All these will provide important guidance for the research on metallogenic rules and controlling structures of the Hu-Bi type copper deposits in the core Cu mining area in Zhongtiao Mountain.

Key words: database; geological map; geological survey engineering; 1∶50 000; Yuanqu map-sheet; Shanxi Province

Data service system URL: http://dcc.cgs.gov.cn

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1 Introduction

Yuanqu map-sheet, Shanxi Province is located in the northern part of Zhongtiao Mountain (Fig. 1). Zhongtiao Mountain lies on the southern margin of the North China Plate, bordering the eastern block of North China in the east, adjacent to Odors Block in the west, and next to Qinling Orogen Belt in the south, thus boasting a unique geotectonic location. It falls within the central orogen of the North China Plate according to the division scheme of the Precambrian tectonic framework (Zhao GC et al., 2002). The Precambrian geological research of Zhongtiao Mountain is significant for exploring the Precambrian tectonic framework and tectonic evolution of the North China Plate (Zhao FQ, 2006).

The metamorphic basement of Zhongtiao Mountain is mainly composed of Sushui complex and the Paleoproterozoic rocks. The Sushui complex serves as the most ancient geological unit in Zhongtiao block. According to zircon U-Pb chronological research on different lithologic units of the Sushui complex, the main magmatic activities of the Sushui complex took place in the Paleoproterozoic, although it contains some Archean rocks (Sun DZ

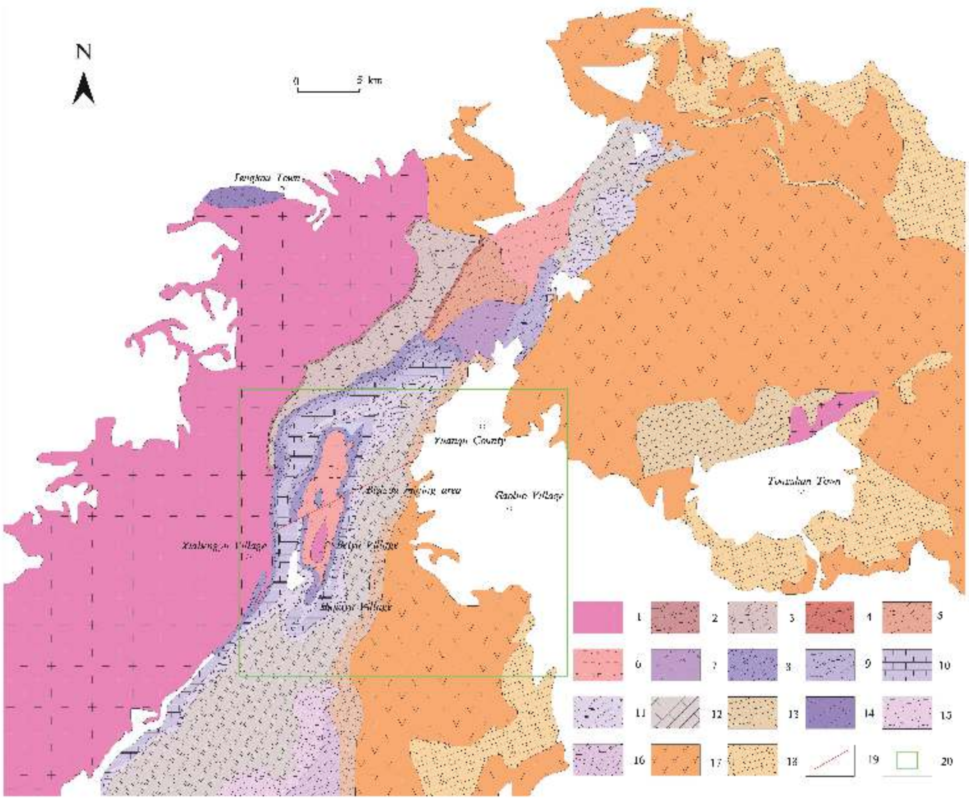

Fig. 1 Geological map of the northern part of Zhongtiao mountain (modified after Zhao FQ et al., 2006)

1—Neoarchean – Paleoproterozoic Sushui complex; 2—Paleoproterozoic Lengkou Formation; 3—Paleoproterozoic Pingtouling Formation; 4—Paleoproterozoic Tongwa Formation; 5—Paleoproterozoic Houshancun Formation; 6—Paleoproterozoic Yuantoushan Formation; 7—Paleoproterozoic Shujinggou Formation + Xijinggou Formation; 8—Paleoproterozoic Luotuofeng Formation; 9—Paleoproterozoic Jiepailiang Formation; 10—Paleoproterozoic Longyu Formation; 11—Paleoproterozoic Yuyuanxia Formation; 12—Paleoproterozoic Bizigou Formation; 13—Paleoproterozoic Yujiashan Formation; 14—Paleoproterozoic Wenyu Formation; 15—Paleoproterozoic Wujiaping Formation; 16—Paleoproterozoic Songjiashan Formation; 17—Mesoproterozoic Xiong'er Group; 18—Mesoproterozoic Ruyang Group; 19—Fault; 20—Location of Yuanqu map-sheet and Hu WX, 1993). However, the Sushui complex was believed to have formed subject to Archean continental magmatic arcs according to regional geological analysis (Bai J et al., 1997). Based on detailed research on the lithogeochemistry and isotopic chronology of the granite in Beiyu Village, Yuanqu County, Shanxi Province, the main part of the Sushui complex in Jiang County was considered to have formed in the Paleoproterozoic (Zhao FQ and Tang M, 1994; Zhao FQ, 1997). Furthermore, as two stages of Neoarchean TTG rocks were newly identified in the Sushui complex in Zhongtiao Mountain, it was inferred that two stages of continental crust growth events occurred in Zhongtiao Mountain in the Neoarchean (Zhang RY et al., 2012, 2013, 2015).

Complete Paleoproterozoic metamorphic strata are exposed in Zhongtiao Mountain, with a number of metamorphic volcanic strata being interbedded. They are extremely rare in other areas of the North China Plate, and thus are ideal for chronostratigraphic research (Zhao FQ et al., 2006). The Paleoproterozoic in Zhongtiao Mountain includes metamorphic volcanic rocks, Jiangxian Group, Zhongtiao Group, and Danshanshi Group, which was agreed by the majority of scholars (Yang CH et al., 2018). As indicated by a series of research results obtained in recent years, sedimentary and volcanic activities in Paleoproterozoic rift setting are widely distributed in Zhongtiao Mountain. Meanwhile, The tectonic interfaces formed owing to Paleoproterozoic major geological events were kept and tectonic-thermal events are very developed in Zhongtiao Mountain. Therefore, Zhongtiao Mountain serves as an ideal area for the research on the structure and evolution of Paleoproterozoic lithosphere.

Yuanqu map-sheet, Shanxi Province is located in the core part of Zhongtiao Mountain metallogenic area, thus boasting favorable geological conditions of mineralization. Since the 1920s when the geological and mineral survey began in this area, previous researchers had conducted extensive research on the sedimentary and volcanic rock formation, the characteristics of metamorphic rocks, metamorphic structures, and chronology of the area through mineral surveys of different properties and extent, thematic researches, as well as regional geological surveys, and geophysical and geochemical exploration on different scales (Sun DZ et al., 1991; Sun JY et al., 1995; Bai J, 1993; Bai J et al., 1997; Zhao FQ et al., 2006). As a result, rich geological and mineral data were obtained, setting a foundation for the 1：50 000-scale regional geological survey in this study. With introduction and development of new geological theories and technologies in recent years, some breakthroughs have been made in the achievements and understandings of the Wutai-Hengshan-Lyuliang area. However, there are still several critical geological issues in terms of metamorphic basement and metallization in Zhongtiao Mountain—one of the typical early Precambrian areas in the North China Plate. The main issues include: the material composition and formation eras of the Sushui complex; the re-understanding, redefinition, and re-division of a Paleoproterozoic stratigraphic system; the definition of the properties, tectonic background, eras, and ore-bearing features of important tectonic interfaces; the division scheme and regional correlation research of Mesoproterozoic and Neoproterozoic boundaries; the confirmation of the properties and formation eras of critical Mesoproterozoic and Neoproterozoic interfaces; the relationship between the volcanic structures of Xiong'er Group and copper deposits; research on the tectonic framework of Zhongtiao Mountain, and the building of the chronological framework of Zhongtiao Mountain. In addition, it is necessary to conduct in-depth research on the geological setting under which different types of copper deposits were formed in Zhongtiao Mountain since main mining areas are facing resource exhaustion with the copper deposits in this area being explored with more efforts in recent years. Therefore, the China Geological Survey conducted a fine 1：50 000-scale geological survey and assessment by taking the golden area of Zhongtiao Mountain as a demonstrative zone, which centered on key mineral types such as Ag, Au, and Mo and highlighted the complicated early-Precambrian geological setting of the area. The purpose was to support strategic actions for prospecting breakthroughs, solve geoscientific technical challenges in Zhongtiao Mountain, and serve the fulfillment of major requirements of social and economic development.

The Database (Table 1; Sun H et al., 2020) is one of the achievements obtained from the geological and mineral survey of Zhongtiao-Xiongershan metallogenic area undertaken by the Tianjin Center of China Geological Survey.

Table 1 Metadata Table of Database (Dataset)

Items	Description
Database (dataset) name	1：50 000 Geological Map Database of Yuanqu Map-sheet, Shanxi Province
Database (dataset) authors	For sedimentary rocks: Sun Hua, Shanxi Institute of Geological Survey For volcanics: Hou Donghong, Shanxi Institute of Geological Survey For magmatites: Liu Weidong, Shanxi Institute of Geological Survey For metamorphic rocks: Zhao Jianxin, 214 Geological Team of Shanxi Provincial Geological Prospecting Bureau For geological structures: Li Jianrong, Shanxi Institute of Geological Survey
Data acquisition time	2016–2018
Geographic area	111°30′–111°45′ E, 35°10′–35°20′ N
Data format	MapGIS
Data size	69.2 MB
Data service system URL	http://dcc.cgs.gov.cn
Fund project	Funded by the geological survey project titled '*1：50 000-scale Regional Geological and Mineral Survey of Jiang County Map-sheet, Yuanqu Map-sheet, and Tongshan Town Map-sheet, Shanxi Province*' initiated by China Geological Survey (No.: DD20160043-01)
Language	Chinese
Database (dataset) composition	The Database consists of 1：50 000 geological map databases and map decorations. The geological map databases include the data of sedimentary rocks, magmatites, volcanics, metamorphic rocks, the Quaternary, dikes, structures, geological boundaries, attitude, lithologic patterns, and various geological codes. The map decorations include index map, histograms, legends, transverse cutting profiles, an intrusion table, and a duty table

2 Methods for Data Acquisition and Processing

2.1 Data Basis

The 1 ∶ 50 000 geological map of Yuanqu map-sheet, Shanxi Province was prepared under the guidance of the '*Technical Requirements for Regional Geological Survey (Scale: 1 ∶ 50 000)*' (DD2019–01), with the '*Standard on Spatial Databases for Digital Geological Maps*' (DD2006–06) as the basis for the building of the Database. The data for Digital Line Graphic (DLG) of Yuanqu map-sheet were provided by National Administration of Surveying, Mapping and Geoinformation of China, while the data of topographic lines were provided by the Shanxi Administration of Surveying, Mapping and Geoinformation in the format of DWG. Relevant data was processed according to existing technical standards by using the software such as the Digital Geological Survey System (DGSS) and MapGIS.

2.2 Data Processing

The Gauss-Kruger projection and Xi'an 1980 were used as the projection system and coordinate system of this map-sheet, respectively. The digital mapping (PRB) database was preliminarily established based on field route survey, during which the points and lines such as geological points, boundary points, geological boundaries, and routes were plotted in the DGSS in the palm-sized personal digital assistant, with the 1 ∶ 25 000 digital topographic map as the base map. Meanwhile, the properties, lithology, and attitude of these points and lines were also observed and input into the DGSS. Afterwards, all of the PRB data of geological points were imported into computers. Then they were processed and mosaic maps were prepared in accordance with applicable specifications. In this way, the 1 ∶ 50 000 geological map of Yuanqu map-sheet, Shanxi Province was completed. In addition, the primitive data maps were plotted with the PRB data acquired in the field. Then the boundaries and formation patterns of stratigraphic units, as well as tectonic morphologies reflecting various formations, were plotted based on the primitive data maps. Afterwards, the boundaries of newly formed geological units were formed by point connecting. As a result, the formation and structure map was prepared (Fig. 2).

3 Description of Data Samples

3.1 Naming of data

The .wp, .wl, and .wt are the suffixes of the files of geological polygons, geological lines, and geological points, respectively.

3.2 Contents in Map Layers

The contents in the master map include sedimentary rock formation, volcanic formation, intrusive formation, metamorphic rock formation, Quaternary, structures, geological boundaries, attitude, and various codes.

The map decorations include index map, histograms, legends, transverse cutting profiles and duty table.

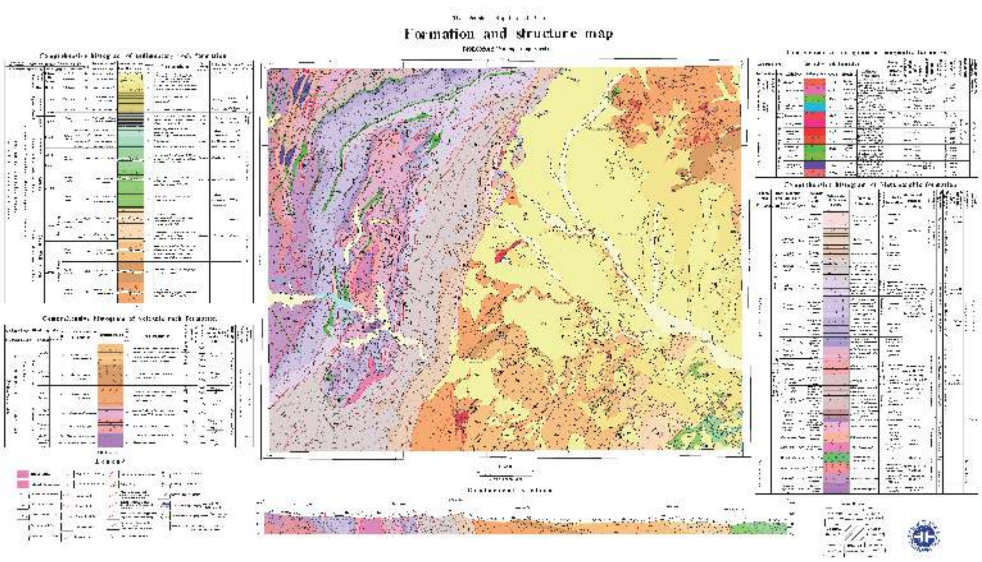

Fig. 2 The 1：50 000 formation and structure map of Yuanqu map-sheet (I49E005015), Shanxi province

3.3 Data Types

Names of entity types: points, lines, and polygons.

Points: symbols and labels of various geological blocks, and geological patterns.

Lines: fault structures, geological boundaries, lithofacies boundaries, etc.

Polygons: sedimentary rocks, volcanics, metamorphic rocks, intrusives, Quaternary, etc.

3.4 Data Attributes

The Database includes the data of geological entity elements, geographical elements, and decoration elements of geological maps. As for the attributes of the geographical elements, the attribute structure used for data collection by the National Administration of Surveying, Mapping and Geoinformation of China was followed. The attributes of geological entity elements were created according to rocks of four major types (sedimentary rocks, volcanics, intrusives, and metamorphic rocks), fault structures, and attitude elements according to the requirements for establishing databases of geological mapping of 1：50 000-scale regional geological survey.

The data attributes of sedimentary rock formation mainly include: chronostratigraphic units, lithostratigraphic units, formation name, formation code, lithological association, stratigraphic eras, formation thickness, formation-related ore-bearing features, rock texture, sedimentary structure, rock colors, sedimentation type, sedimentary facies type, and synsedimentary structure.

The data attributes of volcanic rock formation mainly include: chronostratigraphic units, lithostratigraphic units, formation name, formation code, stratigraphic eras, stratigraphic division, lithological association, formation thickness, formation-related ore-bearing features, volcanic eruption cycle, volcanic eruption type, volcanic rock genetic type, special lithologic intercalations, volcanic facies type, and isotopic age.

The data attributes of intrusion formation mainly include: formation name, formation code, lithological association, formation-related ore-bearing features, rock texture, rock structure, intrusion stages, rock mass attitude, plane morphology, profile morphology, structure features of rock mass emplacement, contact zone characteristics, genetic type, and isotopic age.

The data attributes of metamorphic rock formation mainly include: chronostratigraphic units, lithostratigraphic units, formation name, formation code, lithological association, stratigraphic eras, formation thickness, formation-related ore-bearing features, rock texture, rock structure, protolith formation, metamorphic facies, and metamorphism type.

The data attributes of a fault structure mainly include: fault name, fault type, fault length, fault depth, fault width, fault strike, fault surface dip, fault surface dip angle, fault plane dip angle, fault throw, fault surface morphology, tectonic rock features, movement modes, activity stages, and mechanical properties.

The data attributes of attitude include: attitude type, dip, and dip angle.

4 Quality Control and Assessment of Data

The geological mapping was conducted in accordance with the '*Technical Requirements for Regional Geological Survey (1∶50 000)*' (DD2019–02). The areas with complicated geological conditions were surveyed along denser routes to ensure that the information in the field can be presented on the geological maps completely and objectively. The geological points were acquired on the principle that key geological boundaries, tectonic boundaries, geological blocks related to mineralization, and mineralized alteration zones were fully controlled. To prepare the 1∶50 000 geological map of Yuanqu map-sheet, Shanxi Province, the field survey covered a total route of 587.8 km, 868 geological points, and 1 169 geological boundaries. Thus there is one geological point or one boundary every 304 m of the route on average. Meanwhile, different scales of profiles with a length of 44.9 km were surveyed, trace and rare earth element analysis of silicate were both carried out for 50 samples, thin section identification was conducted for 174 samples, artificial heavy concentrate survey was conducted for 7 samples, and zircon U–Pb dating was conducted for 7 samples. In addition, 400 attitudes and 216 photos were involved as well.

Generally, the contents presented on the map face only include sealed geological blocks with a diameter greater than 100 m, linear geological blocks with a width greater than 50 m and a length greater than 250 m, and fault and fold structures with a length greater than 250 m. All mineralized alteration structures and other mineralized geological blocks were plotted on the 1∶50 000 geological map, regardless of their size. The ones with smaller thickness were expressed by using appropriate patterns or symbols after zooming in or merging. The error in the location of a geological point (i.e., the difference between its location calibrated on the freehand field map and its actual location) should not exceed 25 m in general.

As for the data quality, the self-check rate and mutual check rate of the survey routes for geological mapping were both up to 100%, and the rate of spot inspection conducted by the project team was 30%, thus meeting the requirements of quality management of geological survey projects. During October 26–29, 2016 and November 10–14, 2017, the Tianjin Center of China Geological Survey organized relevant experts to conduct double quality checks in the field. In detail, complete spot inspection was carried out for the work implemented since the commencement of the project, including the progress and quality of the work, main physical workload finished, the achievement progress obtained, and inner quality management. Meanwhile, the work quality was assessed, and the quality check level was rated excellent. During October 22–27, 2018, the Tianjin Center of China Geological Survey organized experts to conduct acceptance check on the survey site of the map-sheet through indoor inspection along with field inspection. As a result, the Yuanqu map-sheet (I49E005015) was scored 92 points according to the comprehensive assessment of the experts.

5 Data Value

The 1：50 000 geological map of Yuanqu map-sheet (I49E005015), Shanxi Province is one of the demonstrative maps prepared during a new round of geological surveys initiated by the China Geological Survey. It was prepared aiming to survey critical geological issues that had existed in Zhongtiao Mountain for many years. On the basis of field geological study, the geochemical data of 54 samples and isotopic chronological data of 7 samples were obtained (Table 2). The time limits and significance of Wutai and Lyuliang (Zhongtiao) tectonic events, especially the tectonic and magmatic thermal events, were explored as a focus by mainly employing the research means of isotope chronology, geochemistry, and metamorphism based on field geological research. Through in-depth research and dissection of the key issues, great progress was made in the properties, eras, and attribution of the Sushui complex; the redefinition, division, and the geological structural research of Proterozoic boundaries, and the division and formation eras of Mesoproterozoic Changcheng System. Meanwhile, the types and characteristics of protolith formation of the metamorphic rocks in the map-sheet were ascertained (Table 3), the formation and tectonic map was plotted correspondingly, and the types and metamorphic facies of the metamorphism were researched in detail. In addition, the mineral association was carefully analyzed, and the metamorphic facies zones were reasonably divided. All these have provided basic data for geological prospecting in the map-sheet, and played a leading role in scientific and technologic innovation. Meanwhile, they have enhanced the capability of mineral and geological survey to serve resource security, social and economic development, and building of ecological civilization.

Table 2 Test and analysis data of the geological map spatial database of Yuanqu map-sheet (I49E005015), Shanxi province

Data type	Data volume	Basic characteristics of data
Petrochemical analysis	54 pieces	14 major elements of volcanic and intrusive rocks
Trace element analysis	54 pieces	14 trace elements of volcanic and intrusive rocks
Rare earth element analysis	54 pieces	15 rare earth elements of volcanic and intrusive rocks
Isotopic age	7 pieces	LA-ICP-MS zircon U–Pb isotopic ages of volcanic and intrusive rocks

Table 3 List of metamorphic rock formations on the 1：50 000 geological map of Yuanqu map-sheet (I49E005015), Shanxi province

Era	Period	Group	Formation/rock mass	Code	Metamorphic rock formation type	Lighologic description	Protolith formation	Metamorphic mineral assemblage	Metamorphism type	Metamorphic facies
Paleoproterozoic	Hutuo	Danshanshi Group	Shanjinhe Formation	Pt_1sj	Conglomerate – quartzite metamorphic formation	Metamorphic conglomerates interbedded with sandy slate and quartzite	Conglomerate – quartz sandstone formation	Ser+Chl+Q	Regional low temperature dynamic metamorphism	Low- – sub-greenschist facies
			Xifengshan Formation	Pt_1xf	Quartzite metamorphic formation	Medium – thick laminated quartzite	Quartz sandstone formation			
			Zhoujiagou Formation	Pt_1z	Conglomerate metamorphic formation	Metamorphic conglomerates	Conglomerate – quartz sandstone formation			
		ZhongtiaoGroup	Yujiashan Formation	Pt_1yj	Thick laminated dolomite metamorphic formation	Dolomite marble and scapolite-dolomite marble interbedded with carbonaceous slate (schist)	Carbonatite formation	St+Bit+Ms+Pl+Q St+Alm+Bit+Ms+Pl+Q Bit+Ms+Q+Pl±Ky Alm+Bit+Ms+Q Alm+Bit+Ms+Pl+Q	Regional dynamic dynamothermal metamorphism	Low hornblende facies – low greenschist facies
			Bizigou Formation	Pt_1b	Schist formation	Carbonaceous schist (slate), sericite schist, two-mica schist, staurolite-garnet-mica schist, and garnet-mica schist, locally interbedded with dichroite schist	Argillaceous rock – carbonatite – basic volcanic rock formation	Alm+Bi±Chl Cc+Bit±Scp Ser+Ab+Q±Chl Bit+Ms+Q±Pl±Chl Cc+Q±Tr+Scp		
			Yuyuanxia Formation	Pt_1yy	Thick laminated dolomite metamorphic formation	Dolomite marble and scapolite-dolomite, with branched columnar stromatolites occurring in the upper part	Carbonatite formation			

Continued table 3

Era	Period	Group	Formation/rock mass	Code	Metamorphic rock formation type	Lighologic description	Protolith formation	Metamorphic mineral assemblage	Metamorphism type	Metamorphic facies
Paleoproterozoic	Hutuo	ZhongtiaoGroup	Longyu Formation	Pt_1ly	Sandy slate – quartzite – marble metamorphic formation	Calcareous slate interbedded with dolomite marble in the upper part; sandy slate interbedded with quartzite in the lower part	Argillaceous rock – carbonatite formation	St+Bit+Ms+Pl+Q St+Alm+Bit+Ms+Pl+Q Bit+Ms+Q+Pl±Ky Alm+Bit+Ms+Q Alm+Bit+Ms+Pl+Q Alm+Bi±Chl Cc+Bit±Scp	Regional dynamic dynamothermal metamorphism	Low hornblende facies – low greenschist facies
			Jiepailiang Formation	Pt_1j	Quartzite – conglomerate metamorphic formation	Quartzite, with the bottom consisting of metamorphic conglomerates	Quartz sandstone – conglomerate formation	Ser+Ab+Q±Chl Bit+Ms+Q±Pl±Chl Cc+Q±Tr+Scp		
		JiangxianGroup	Xijinggou Formation	Pt_1x	Metabasic volcanic formation	Metabasalts (biotite-hornblende schist, scapolite-biotite schist, and biotite schist)	Basic volcanic formation	Alm+St+Bit+Ky+Ms+Q Alm+Bit+Ms+St+Q+ PlKy+Bit+Ms+Q Alm+Bit+Ms(Ser)+Q Alm+Cht+Ms(Ser)+Q Scp+Bit+Hb+Q	Regional dynamic dynamothermal metamorphism	Low hornblende facies – Low greenschist facies
			Shujinggou Formation	Pt_1s	Metamorphic acidic volcanic formation	Metamorphic rhyolite and metamorphic rhyolitic dacite	Acidic volcanic formation	Cht+Chl+Ser+Q Bit+Chl+Ser+Q		
			Tongwa Formation	Pt_1t^3	Al-rich sericite schist metamorphic formation	Staurolite-garnet-mica schist	Al-rich argillaceous rock formation			

Continued table 3

Era	Period	Group	Formation/rock mass	Code	Metamorphic rock formation type	Lighologic description	Protolith formation	Metamorphic mineral assemblage	Metamorphism type	Metamorphic facies
Paleoproterozoic	Hutuo	JiangxianGroup	Tongwa Formation	Pt_1t^2	Sericite-quartz schist and sericite-quartz metamorphic formation	Sericite-quartz schist and sericite-quartz	Argillaceous sandy formation	Alm+St+Bit+Ky+Ms +Q Alm+Bit+Ms+St+Q+ PlKy+Bit+Ms+Q Alm+Bit+ Ms(Ser)+Q Alm+Cht+Ms(Ser)+ Q Scp+Bit+Hb+Q Cht+Chl+Ser+Q Bit+Chl+Ser+Q	Regional dynamic dynamothermal metamorphism	Low hornblende facies – Low greenschist facies
				Pt_1t^1	Al-rich sericite schist – carbonaceous sericite schist metamorphic formation	Carbonaceous sericite schist, carbonaceous garnet-mica schist, and carbonaceous staurolite-garnet-mica schist	Al-rich argillaceous rock formation			
			Pingtouling Formation	Pt_1p	Quartzite –mica schist metamorphic formation	Quartzite, with the middle part containing cyanite and garnet	Argillaceous sandy formation			
			Lengkou Formation	$Pt_1l.$	Biotite schist and hornblende-biotite schist metamorphic formation	Biotite schist and hornblende-biotite schist	Basic volcanic formation	Hb+Ab+Q	Regional dynamic dynamothermal metamorphism	Hornblende facies
			Henglingguan granite	Pt_1Hgn	Adamellite formation	Metamorphic adamellite	Adamellite formation	Hb+Ab+Q		Low hornblende facies

Continued table 3

Era	Period	Group	Formation/rock mass	Code	Metamorphic rock formation type	Lighologic description	Protolith formation	Metamorphic mineral assemblage	Metamorphism type	Metamorphic facies
Paleoproterozoic	Hutuo		Donggou gneiss	Pt_1Dgn	Diorite gneiss formation	Biotite-hornblende plagiogneisses	Formation of tonalites of the tonalite–trondhjemite–granodiorite (TTG) series	Hb+Alm+Pl+QHb+Pl+Q	Regional dynamic dynamothermal metamorphism	High hornblende facies
			Beiyu gneiss	Pt_1Bgn	Trondhjemitic gneiss formation	Trondhjemitic gneiss	Formation of trondhjemites of the TTG series			
Neoarchean			Metabasic rocks	Ar_3N	Metabasic dykes	Metagabbro and metamorphic diabase	Basic dike	Hb+Pl+Q		Hornblende facies
			Xiezhou gneiss	Ar_3Hgn	Adamellite gneiss formation	Biotite monzogneiss	Formation of granodiorites of the TTG series	Pl+Kf+Bit+Sill+Hb+Pl+Q		High hornblende facies
			Xiyao gneiss	Ar_3Xgn	Tonalite gneiss formation	Banded biotite plagiogneisses	Formation of tonalites of the TTG series	Pl+Kf+Bit+Sill+Hb+Pl+Q		
			Chaijiayao supracrustal rocks	Ar_3csr	Rhyolite metamorphic formation	Metamorphic rhyolite	Acidic volcanic formation	Pl+Kf+Bit+Sill+Hb+Pl+Q		

Note: Ser: serpentine; Chl: chlorite; Q: quarz; St: staurolite; Alm: almandine; Bit: biotite; Ms: muscovite; Tr: tremolite; Pl: plagioclase; Ky: kyanite; Cht: chloritoid; Cc: calcite; Scp: scapolite; Hb: hornblende; Ab: albite; Kf: potassium feldspar; Sill: sillimanite.

5.1 New Understanding of Sushui Complex

The Sushui complex in Yuanqu map-sheet, Shanxi Province was broken into different geological units of the Neoarchean and Paleoproterozoic, providing bases for re-understanding the formation and evolution of metamorphic basement in the map-sheet.

The Neoarchean metamorphic rock series was divided into four geological block units, namely Chaijiayao supracrustal rocks, Xiyao gneiss (TTG), Xiezhou calc-alkaline gneiss (CA series), and metamorphic gabbros. The Chaijiayao supracrustal rocks (metamorphic rhyolites) yielded a new age of 2 511 ± 13 Ma. Xiyao gneiss was determined to be intruded by Zhaizi gneiss, Donggou gneiss, and Henglingguan metamorphic granite at 2 553 ± 21 Ma, 2 543 ± 21 Ma, and 2 551 ± 2.7 Ma, respectively in this study. Based on the new age of Chaijiayao supracrustal rocks, as well as the intrusion information of Xiyao gneiss including the geological bases, intrusion ages, and petrochemical characteristics, Xiyao gneiss was considered to have possibly formed owing to the partial melting of juvenile crust in the late Archean (~2.7 Ga). Xiezhou gneiss (2 530 ± 13 Ma; this study) was identified in the map-sheet for the first time. As indicated by the petrochemical characteristics, Xiezhou gneiss was comprised of I-type, high-K, calc-alkaline granite and was possibly formed due to the partial melting of juvenile crust occurring at 2.5 –2.8 Ga. This further proved that the Neoarchean block in Zhongtiao Mountain was formed in the island-arc tectonic system. Therefore, it can be inferred that continental crust accretion events may have occurred in the map-sheet at ~2.5 Ga (i.e., the map-sheet had been cratonized at the end of the Archean).

A stage of magmatic thermal event at 2 350 –2 200 Ma was newly discovered. It was broken into different rock units such as the Beiyu gneiss, Donggou gneiss, Henglingguan gneiss, metamorphic ultramafic intrusions, and metamorphic gabbros. The Beiyu metamorphic trondhjemites and Henglingguan metamorphic granite yielded new ages of 2 313 ± 13 Ma and 2 235 ± 13 Ma, respectively. As for petrochemical characteristics, Donggou gneiss and Beiyu gneiss were found to be similar to Archean TTG rocks and adakites in general, showing the characteristics of synorogenic granites. Meanwhile, Henglingguan metamorphic granites exhibit the geochemical characteristics of typical calc-alkaline granites, and thus possibly represent the products of synorogeny – post-orogeny stage.

5.2 New Understanding of Jiangxian Group

The Jiangxian Group in Yuanqu map-sheet, Shanxi Province was divided into Henglingguan and Tongkuangyu subgroups, and their formation age was adjusted from the Neoarchean to the Paleoproterozoic. The Henglingguan subgroup of the Jiangxian Group was ascertained to be in angular unconformable contact with the Zhongtiao Group. The volcanics of Shujinggou Formation of Jiangxian Group yielded new ages of 2 137 ± 16 Ma and 2 147 ± 13 Ma, thus accurately constraining the lower sedimentary boundary of the Jiangxian Group. All these provided data for research on the sedimentary setting and time limits of Hutuo rift basin.

5.3 New Understanding of Xiong’er Group

The Mesoproterozoic Xiong’er Group in Yuanqu map-sheet, Shanxi Province was divided again. Jidanping Formation was identified in Zhongtiao Mountain for the first time by mapping, and the contact relationships of the top and bottom of the Xiong’er Group were ascertained. Furthermore, a batch of chronological data was newly obtained, and thus the time limits of volcanic activities in the Xiong’er Group were determined. All these provided the bases for determining the properties and regional tectonic significance of the “Lyuliang Movement”.

In this study, the subvolcanic rhyolites that intruded Xushan Formation yielded new ages of 1 788 ± 14 Ma (Dongzhoujiawa) and 1 777 ± 15 Ma (Louzizhuang). Meanwhile, the acidic volcanics (lava) in Jidanping Formation yielded a new age of 1 777 ± 14 Ma (Jiabaoshan).

5.4 Large Extensional Detachments and Metamorphic Core Complex being Newly Identified

A stage of Paleoproterozoic large extensional detachments and metamorphic core complex were identified in Yuanqu map-sheet, Shanxi Province, which control the spatial distribution of the whole Hutuo system in Zhongtiao Mountain (including the Jiangxian and Zhongtiao Groups) and the formation rule of Hu-Bi type copper deposits. Affected by the main stage of Paleoproterozoic structures, they display complex structural patterns in terms of spatial morphology, which vary in different structural zones. In general, they can be generalized as the Beiyu metamorphic core complex, the extensional ductile shear zone between the Sushui complex and the overlying Jiangxian Group (Zhongtiao Group), and the detachment system in the area of “Shangyupo brachyanticline”.

5.4.1 Formation Era of Main Shear Zone Being Restricted to the Early Paleoproterozoic

The bottom horizon of the Jiangxian and Zhongtiao Groups was ascertained to be in contact with the underlying gneiss basement through ductile faults, with serious stratigraphic gap. The footwall has been strongly transformed into mylonite schist and mylonite gneiss, with massive rocks being fully foliated. As a result, typical mylonite and structural schist series were formed. In contrast, as for the overlying Jiangxian and Zhongtiao Groups, bedding recumbent folds and a bedding foliated zone represented by a folding layer system have been formed within them. As indicated by a large number of marks of shear movements, the shear direction of the main shear zone is the normal sliding of the hanging wall (SE-trending) along a NW-SE trend. The Henglingguan rock mass near the main shear zone yielded an age of 2 231 ± 86 Ma, the metamorphic volcanic rocks of Tongkuangyu subgroup of Jiangxian Group yielded the ages of 2 137 ± 16 Ma and 2 147 ± 13 Ma, and the Yanzhuang adamellites that intruded into the Tongwa Formation of the Jiangxian Group yielded an age of 2 128 ± 14 Ma. All these restricted the formation era of the main shear zone to the extensional stage of the early Paleoproterozoic.

5.4.2 Confirmation of the Structure and Boundary Fault Characteristics of Beiyu Metamorphic Core Complex

The main body of the Beiyu metamorphic core complex is composed of the rock mass (core) of Beiyu gneiss and detachment faults. The Beiyu gneiss shows a dome-shaped uplift, with the rocks exhibiting strong plastic deformation as well as obvious flow structure and schistosity. The rocks inside the shear zone are typical mylonites or ultramylonites (similar to structural schist in the field), which were formed in the Paleoproterozoic (2 313 ± 13 Ma, newly obtained in this study). The detachment faults occur between the Beiyu gneiss rock mass and the Jiangxian Group. The Jiangxian Group suffers serious stratigraphic gap in the lower horizon and strong brittle and ductile deformation. The difference in the deformation behaviors reflects the long-term uplifting of the metamorphic basement. According to analysis of the features of the shear zone such as two sausage structures, S–C fabric, and small folds, the shear zone was formed subject to the left-lateral shearing mechanism, which is the activity mechanism of normal faults featuring the eastern (hanging) wall sliding downward and the western (foot) wall moving upward.

5.4.3 The Detachment System in the "Shangyupo Brachyanticline" Area Being Determined to Feature Three-Layer Structural Pattern

The Shangyupo brachyanticline in the Yuanqu map-sheet shows complicated structural framework, which is mainly caused by later fold superimposition onto the regional detachment faults of this stage. The main fault system is a multi-level large-scale ductile detachment fault system that has developed after inheriting different lithologic features of the Zhongtiao Group. It is composed of a main fault and several branch faults. There are three key faults, among which the one at the bottom of the Zhongtiao Group is the main detachment fault and the two on the top and bottom interfaces of the Bizigou Formation are branch detachment faults. All of them jointly constitute the detachment fault system. They are arranged in parallel (in plane view) and form a three-layer structural pattern (in profile view) after the later fold superimposition is removed (Fig. 3).

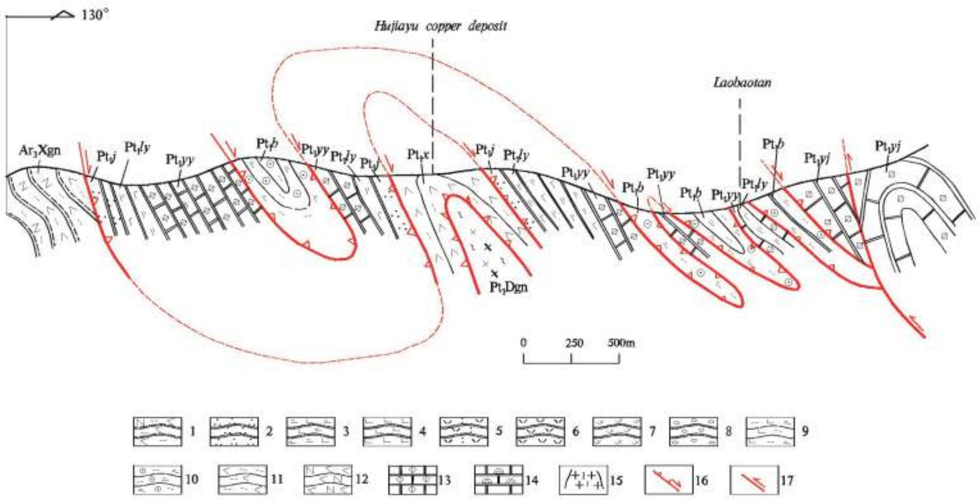

Fig. 3 Hujiayu copper deposit–Laobaotan geological structural profile in Yuanqu map-sheet

1—Biotite-hornblende-plagioclase gneiss; 2—Quartzite; 3: Calcareous sericite schist; 4—Calcareous slate; 5—Metamorphic rhyolite tuff; 6—Metamorphic rhyolite; 7—Metamorphic dacite; 8—Metamorphic conglomerate; 9—Calcareous two-mica schist; 10—Garnet-bearing two-mica schist; 11—Biotite-hornblende schist; 12—Plagioclasite hornblende (schist); 13—Dolomite marble; 14—Stromatolite marble; 15—Gneissic granite; 16—Detachment fault in the basement of Zhongtiao Mountain; 17—Reverse fault

5.5 New Achievements made in Geographic Base Map and Database

The geographic base map of Yuanqu map-sheet with high precision and new data was developed based on the new 1：50 000 digital geographical base map and database by fully absorbing and complementing the latest geographic information in recent years, with Xi’an 1980 as the unified coordinates system. Meanwhile, the spatial database was established. The databases established and delivered include the PRB database of four 1：25 000 map-sheets, the database of primitive data map, and the spatial database of 1：50 000 geological map achievements, with complete various data being achieved and the expression means of map face meeting relevant specifications (Li HY et al., 2018). In this way, relevant technical requirements of database building were met and these databases will provide data to enhance the social service of regional publicly available geological data.

6 Conclusion

(1) The 1：50 000 geological map of Yuanqu map-sheet (I49E005015), Shanxi Province is a demonstrative map developed during the geological and mineral survey deployed in the core mining area in Zhongtiao Mountain by the China Geological Survey. A new round of geological mapping was conducted in order to address major geological issues existing in Zhongtiao Mountain, during which the expression of metamorphic geology and tectonic results were highlighted. The 1：50 000 geological map will provide important guidance for research on basic geological setting and mineral geology of Zhongtiao Mountain.

(2) The material composition of the metamorphic basement in Zhongtiao Mountain was primarily ascertained by breaking up the Sushui complex in the area. The Paleoproterozoic boundary in Zhongtiao Mountain was re-determined and a new division scheme of the boundary was put forward. The volcanic structures, lithology and lithofacies, and volcanic strata of the Mesoproterozoic Xiong’er Group were mapped, and isotopic dating was conducted for the group. As a result, the lower boundary of the Mesoproterozoic in the area was restricted. Furthermore, the characteristics of metamorphic rock formation were systematically summarized, and three stages of tectonic superimposition patterns of the Paleoproterozoic in Zhongtiao Mountain were proposed. The new results and data are of high value for re-evaluating the stratigraphic tectonic framework of Zhongtiao Mountain.

(3) The 1：50 000 geological map of Yuanqu map-sheet was completely prepared and the corresponding spatial database was established. Meanwhile, the PRB database of four 1：25 000 map-sheets and the database of primitive data map were also established and delivered. In this way, complete various data were achieved, the expression means of map face met relevant specifications, and relevant technical requirements of database building were met. These databases will provide data to enhance the social service of regional publicly available geological data.

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References

Bai Jin. 1993. Precambrian geology and Pb-Zn mineralization in the northern margin of the North China Platform[M]. Beijing: Geological Publishing House (in Chinese).

Bai Jin, Yu Zhixin, Yan Yaoyang, Dai Fengyan. 1997. Precambrian geology of Zhongtiao Mountains[M]. Tianjin: Tianjin Science and Technology Publishing House (in Chinese).

Li Hongying, Ye Huishou, Yang Lei, Geng Yanguang, Bi Minfeng, Yin Dewei, Xue Shengsheng, Jian Wei, Fan Chenglong, Wang Mengqi, Zhao Nan. 2018. Practice and reflection on the special mapping of precambrian copper deposits in Zhongtiao Mountains, Shanxi Province[J]. Geological Bulletin, 37(2–3): 271−282 (in Chinese with English abstract).

Sun Dazhong, Hu Weixing. 1993. The Precambrian geochronological framework and chronotectonic structure of the Zhongtiao Mountains[M]. Beijing: Geological Publishing House (in Chinese).

Sun Dazhong, Li Huimin, Lin Yuanxian, Zhou Huifang, Zhao Fengqing, Tang Min. 1991. Precambrian geochronology, chronotectonic framework and model of chronocrustal structure of the Zhongtiao Mountains[J]. Acta Geologica Sinica, 65(3): 216−231 (in Chinese).

Sun Jiyuan, Ji Shukai, Zhen Yunqing. 1995. The Zhongtiao Rift Copper Deposit[M]. Beijing: Geological Publishing House (in Chinese).

Sun Hua, Hou Donghong, Liu Weidong, Zhao Jianxin, Li Jianrong. 2020. 1：50 000 Geologic Geological Map Database of Yuanqu Map-sheet, Shanxi Province[DB/OL]. Geoscientific Date & Discovery Publishing System. (2020-06-30). DOI:10.35080/data.A.2020.P13.

Yang Chonghui, Du Lilin, Song Huixia, Ren Liudong, Miao Peisen, Lu Zenglong. 2018. Stratigraphic division and correlation of the Pleoproterozoic strata in the North China Craton: A review[J]. Acta Petrologica Sinica, 34(4): 1019−1057 (in Chinese with English abstract).

Zhao Guochun, Sun Min, Wilde SA. 2002. Characteristics of tectonic units in North China Craton basement and early Proterozoic assemblage[J]. Science in China(Series D), 32(7): 538−549 (in Chinese).

Zhao Fengqing. 2006. Chronology and geochemistry constraints on the evolution of the Paleoproterozoic in the Zhongtiao Mountains area of Shanxi[D]. Beijing: Ph.D. Dissertation China University of Geosciences(Beijing) (in Chinese with English abstract).

Zhao Fengqing, Tang Min. 1994. The Rock Geochemistry of Beiyu granite in the southern part of Shanxi Province, China[J]. Journal of Geology and Mineral Resources of North China, 9(3): 271−280 (in Chinese).

Zhao Fengqing. 1997. Isotopic age and geochemistry characteristics of the Beiyu trondhjemites in the Zhongtiao area[J]. Progress in Precambrian Research, 20(1): 44−50 (in Chinese).

Zhao Fengqing, Li Huimin, Zuo Yicheng, Xue Keqin. 2006. Zircon U-Pb ages of Paleoproterozoic granitoids in the Zhongtiao Mountains, southern Shanxi, China[J]. Geological Bulletin of China, 25(4): 442−447 (in Chinese with English abstract).

Zhang Ruiying, Zhang Chengli, DiWu Chunrong, Sun Yong. 2012. Zircon U –Pb geochronology, geochemistry and its geological implications for the Precambrian granitoids in Zhongtiao Mountain, Shanxi Province[J]. Acta Petrologica Sinica, 28(11): 3559−3573 (in Chinese with English abstract).

Zhang Ruiying, Zhang Chengli, Sun Yong. 2013. Crustal reworking in the North China Craton at ~ 2.5 Ga: Evidence from zircon U–Pb ages, Hf isotopes and whole-rock geochemistry of the TTG gneisses in the Zhongtiao Mountain[J]. Acta Petrologica Sinica, 29(7): 588−597 (in Chinese with English abstract).

Zhang Ruiying. 2015. The composition and evolution of the Sushui complex in the Zhongtiao Mountains area of the sourthern North China Craton[D]. Xi’an: Doctoral dissertation, Northwestern University (in Chinese with English abstract).