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巴西圣弗朗西斯科克拉通地质演化与重要成矿作用

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摘 要:【研究目的】本文旨在梳理构建巴西圣弗朗西斯科克拉通构造演化过程,概述与之成矿作用地质背景及矿床成矿系列的耦合关系,并查明典型矿床的时空分布,目的是服务于克拉通演化与成矿理论。**【研究方法】**本文在中巴合作开展野外地质调查的基础上,结合巴西圣弗朗西斯科克拉通基底太古宙片麻岩和元古代的碎屑岩锆石U-Pb、Sm-Nd同位素年代学等文献资料,初步归纳出圣弗朗西斯科克拉通重大地质构造演化事件和重要成矿作用。**【研究结果】**圣弗朗西斯科克拉通4个重要地质演化过程:(1)太古宙3.5 Ga前克拉通古陆核与微陆块形成,3.3~2.9 Ga和2.8~2.5 Ga间则由克拉通北区的盖维奥、索布拉迪纽、塞里尼亚和吉基耶等4个古陆核及南区的近圆形古陆核相互碰撞、拼合和绿岩–增生造山岩浆作用而形成稳定的克拉通陆块;(2)2.5~1.9 Ga古元古代泛亚马逊造山岩浆作用;(3)1.78~1.20 Ga克拉通基底隆升与裂谷改造阶段,形成大量基性岩墙群及陆内非造山型岩浆,完成陆块增厚和最终克拉通化;(4)新元古代克拉通边缘经历巴西利亚/泛非运动(0.64~0.54 Ga)改造,又形成巴西利亚等6个活动造山带。圣弗朗西斯科克拉通形成4期重要成矿作用及相应矿床成矿系列:(1)太古宙(2.5 Ga前)形成绿岩型金矿、苏必利尔湖型硅铁建造为主的变质火山–沉积矿床等成矿系列;(2)古元古代早中期(2.5~1.8 Ga)形成与(超)基性岩相关的铜镍钴硫化物矿床、VMS型铅锌银矿床、IOCG等系列矿床;(3)固结纪–中元古代(1.8~1.0 Ga)形成与非造山岩浆作用相关的铌钽矿、铀矿床,与陆内(缘)裂谷型的钒–钛–铁矿床等系列;(4)新元古代(1.0~0.54 Ga)主要形成铁锰矿、砂锡矿及磷矿等矿床,包括古陆缘–浅海沉积环境有关的(冲积)金刚石砂矿等系列矿床。**【结论】**构建了巴西圣弗朗西斯科克拉通4个重要地质演化过程,相应划分出4期重要成矿作用。

关 键 词:圣弗朗西斯科克拉通;构造演化;成矿作用;成矿系列;巴西

创 新 点:本文高度系统梳理了巴西圣弗朗西斯科克拉通地质演化和重要成矿作用过程。这一研究不仅构建了相关的理论体系,服务于克拉通演化与成矿理论的发展,而且对中国企业在巴西境外投资找矿预测具有重要的参考作用。

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Geological evolution and important mineralization of São Francisco Craton in Brazil

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Abstract: This paper is Geological evolution and important mineralization of São Francisco Craton in Brazil.
[Objective] This paper aims to sort out and construct the tectonic evolution process of the São Francisco Craton in Brazil, outline the coupling relationship with its metallogenic geological setting and ore deposit series, and identify the temporal and spatial distribution of typical deposits, in order to serve the theory of craton evolution and ore formation. **[Methods]** Based on the field geological survey conducted in China- Brazil cooperation, and combined with the zircon U-Pb and Sm-Nd isotope chronology of basement Archean gneiss and Proterozoic detrital rocks of the São Francisco Craton in Brazil, this paper summarizes the major geological tectonic evolution events and important mineralization processes of the São Francisco Craton. **[Results]** Four important geological evolution process of the São Francisco Craton were preliminarily constructed:(1)Before 3.5 Ga, the formation of paleo continental nuclei and microcontinental masses, between 3.3 ~ 2.9 Ga and 2.8 ~ 2.5 Ga, the four paleo continental cores of Archean Gavião block, Sobradinho block, Serrinha block, Jequié block in the north and the nearly circular paleo continental nuclei in the south collided, stitched and proliferated the greenstone-arc magma belt to form a stable cratonic mass. (2) 2.3 ~ 1.9 Ga Paleoproterozoic Pan-Amazonian orogenic arc magmatic activity. (3) 1.78 ~ 1.20 Ga basement uplift, rift stage, forming a large number of basic dikes and non-orogenic magmatism activities and other transformation processes to complete the thickening of landmass and cratonization. (4) Forming 6 active orogenic belts such as Brazilian orogenic belt, the Neoproterozoic craton margin underwent the transformation of the Brasilia / Pan-African movement(0.64 ~ 0.54 Ga).São Francisco craton has formed 4 important mineralization and corresponding deposit metallogenic series :(1)Archean mineralization(>2.5 Ga)formed metamorphic volcano-sedimentary metallogenic series such as greenstone-type gold deposits and Lake Superior-type iron deposits(BIF).(2)The early-middle Paleoproterozoic mineralization (2.5 ~ 1.8 Ga) formed Cu-Ni-Co sulfide deposits, Pb-Zn volcanogenic massive sulfide (VMS) deposits, and iron oxide-copper-gold(IOCG) deposits related to (super) mafic rocks. (3) Mesoproterozoic-Consolidated mineralization(1.8 ~ 1.0 Ga)formed series of deposits such as V-Ti-Fe deposits related to its intracontinental(marginal)rifts, Nb-Ta and Cu deposits related to non-orogenic magmatism.(4)The Neoproterozoic mineralization(1.0 ~ 0.54 Ga)formed Fe-Mn, alluvial tin and P deposits,including(alluvial)diamond placer deposits related to paleo continental margin-neritic sedimentary environment. Key words: São Francisco Craton; tectonic evolution; metallogenesis; metallogenic series; Brazil. **[Conclusions]** Four important geological evolution processes of the São Francisco Craton in Brazil have been constructed, and four important metallogenic periods have been divided accordingly.

Key words: São Francisco Craton; tectonic evolution; metallogenesis; metallogenic series; Brazil

Highlights: In this paper, the geological evolution and important metallogenic processes of the São Francisco Craton in Brazil are systematically reviewed. This study not only establishes the relevant theoretical system, serves the development of craton evolution and metallogenic theory,but also has an important reference role for Chinese enterprises to invest in prospecting and forecasting in Brazil.

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巴西圣弗朗西斯科克拉通(São Francisco Craton,以下简称"SFC")是南美地区五个古老克拉通之一,属于非洲中西部刚果克拉通的西延部分(Trompette,1994)(因大西洋裂解而分开),最长处约1 100 km,最宽约900 km,面积约470 000 km^2,主要分布于巴西米纳斯吉拉斯州和巴伊亚州内(图1a)。SFC最早由Almeida提出,后来的地球物理资料精准确定了其边界、地壳厚度及周边的巴西利亚/泛非运动(Brasiliano /Pan-African,0.64 ~ 0.54 Ga)形成的造山带位置(Almeida,1997)。

SFC据其基底岩石组合特征(Allen,1993; Ezequiel, 2019; Peucat, 2002; Barbosa, et al., 2002),一般将其划分为南、北2区。北区主要包含盖维奥(Gavião)、索布拉迪纽(Sobradinho)、塞里尼亚(Serrinha)和吉基耶(Jequié)4个古陆核的地块,大约在2.1 ~ 2.0 Ga完全拼合在一起(Alkmim, 2005);南区则包括"铁四角"(Quadrilátero Ferrífero,以下简称"QF")条带状铁建造(Banded Iron Formation,以下简称"BIF")区及

其西南部的古陆核。除东部大西洋沿岸外，整个SFC边缘被新元古代造山带所环绕，包括东北部塞尔吉帕诺(Sergipanao)、北部里奥普雷图(Rio Preto)和里亚舒多蓬塔尔(Riacho do Pontal)、西部巴西利亚(Brasiliano)、南部里贝拉(Ribeira)、东南部阿拉苏阿伊(Araçuaí)等造山带(图1)。这些克拉通古陆核及其边缘造山带记录了太古宙SFC古陆块形成、碰撞、拼合及弧-陆岩浆增生、早期的克拉通化等构造演化史，期间又经历了古元古代泛亚马逊造山(Trans-amazonian Orogeny)弧岩浆活动及基底挤压隆升、裂谷事件，及上侵了大量基性岩墙群及陆内非造山型岩浆活动，完成最终的克拉通化。新元古代持续至寒武纪早期的巴西利亚/泛非运动使SFC边缘又经历了诸如里奥普雷图等系列造山活动，并遭受新元古代

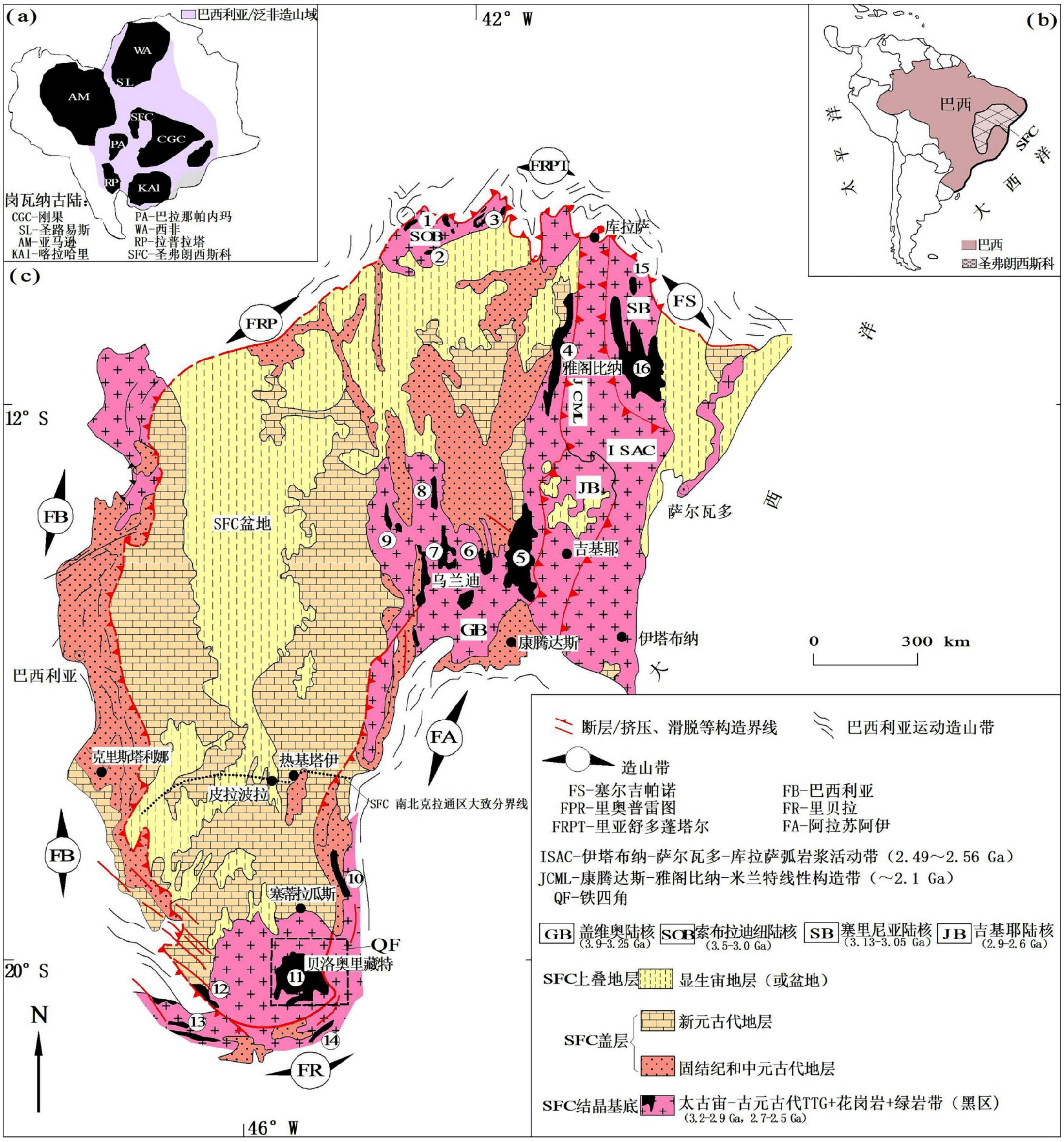

图1 巴西圣弗朗西斯科克拉通地质简图(据Misi, 2005; Alkmim, 2005)

Fig.1 Geological map of the São Francisco Craton, Brazil

图中圆圈中1-13编号代表SFC绿岩带：1.拉戈阿德阿雷格里；2.布雷罗-科洛米；3.萨利特-索布拉迪尼奥；4.蒙多诺沃；5.康腾达斯-米兰特；6.乌姆布拉纳斯，布鲁马多，伊比蒂拉-乌比拉萨巴-格拉豪；7.利西尼奥·德·阿尔梅达；8.博基拉；9.里亚乔·桑塔纳；10.帕拉乌纳；11.达斯韦拉斯；12.皮乌姆希；13.福塔莱萨-莫罗；14.巴巴塞纳；15.卡坪；16.伊塔皮库鲁；a.大部分冈瓦纳古陆及泛非造山带；b.SFC在南美巴西位置；c.前寒武纪圣弗朗西斯科克拉通

沉积盖层(表壳岩系)剥蚀作用,同期的构造岩浆活动减弱。

SFC构造演化复杂且岩石类型多样,太古宙-古元古代结晶基底主要由英云闪长岩-奥长花岗岩-花岗闪长岩(TTG)组合和花岗岩-绿岩带构成,与上覆中-新元古代硅质碎屑岩等沉积盖层共同形成典型的克拉通"基底+盖层"结构。SFC内灰色片麻岩套(TTG)与古陆核增生演化存在彼此关联,为古陆壳残存部分,它们与绿岩带-花岗岩圈共同构成SFC的基底,并经历太古宙-新元古代一系列构造演化作用,这些重要阶段性的地质构造演化作用造成了相关的重要成矿作用,造就并蕴藏了SFC丰富的矿产资源,形成了南美地区极具典型架构和成矿特色的克拉通。

SFC地质演化与成矿作用研究有许多科学问题亟待解决,如SFC残存的古陆核,灰色TTG片麻岩和绿岩带对了解、研究地球早期古陆核形成与增生机制有重要启示价值。另外SFC内为何会蕴藏如此巨量金属矿源,其运移-聚集成矿机制又是什么,克拉通演化与其矿床时空耦合规律如何等等?本文基于中国、巴西地质调查局地学合作项目及野外地质地球化学调查,充分结合并利用SFC太古宙基底片麻岩和TTG及盖层碎屑锆石U-Pb年代学、Sm-Nd同位素等文献资料,旨在梳理构建SFC构造演化过程,概述与之成矿作用地质背景及矿床成矿系列的耦合关系,初步查明典型矿床的时空分布,目的是服务于克拉通演化与成矿理论,对指导中国企业今后在巴西境外投资找矿预测、勘探具有借鉴作用。

1 太古宙SFC古陆核

SFC有南、北两个古陆核区,但其界线已被显生宙形成的SFC盆地盖层所掩盖,大致的界线可能位于皮拉波拉(Pirapora)裂谷槽(图1c)。北部的古陆核区分布面积较大,主要分布在帕拉米林(Paramirim)裂陷槽,或断续出露在SFC盆地边缘,由4个太古宙次级古陆核区组成的,并以康腾达斯-雅阁比纳-米兰特(Jacobina-Contendas- Mirante,以下简称"JCML")构造带为界(Wilson, 2017; Rios, et al.,2009),分为西部的盖维奥、索布拉迪纽和东部的塞里尼亚、吉基耶等4个次级太古宙古陆核区(图1c,图2)(Pierre, et al., 1990),并以盖维奥古陆核最古老(Barbosa, et al.,

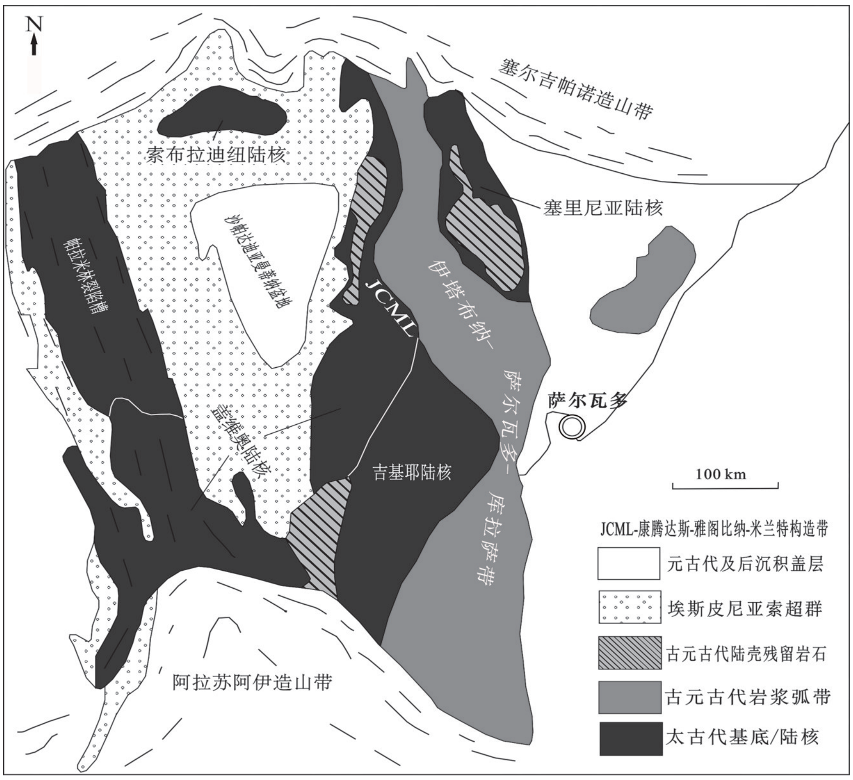

图2 圣弗朗西斯科克拉通北区地质构造单元略图(Wilson,2017)

Fig.2 Geologic sketch of the north segment of the São Francisco Craton

2002）。南部的古陆核区则出露在贝洛奥里藏特（Belo Horizonte）QF西南区（图1c、图3），由中高级变质、变质杂岩等共同构成近圆形古陆核区（包括QF）。这些古陆核主要为太古宙TTG–花岗岩–绿岩岩石组合，受多期造山构造运动叠加而发生变质变形改造，或原地受到晚期花岗岩类、辉长岩–斜长岩及（超）镁铁质基性岩墙的侵入（Cahen, et al.,1984; Teixeira, 1991; Ernst, et al., 2013）。

1.1 北区古陆核特征

盖维奥古陆核：大致以环形穹窿状分布，东侧是以JCML构造带为界，南部则以新元古代阿拉苏阿伊造山带为界，岩石组成包括肢解残存的变质火山沉积岩系（绿岩带）、角闪岩、混杂岩和侵入其中的多种灰色片麻岩套及（钠、钾质）花岗岩与英云闪长岩、奥长花岗岩等TTG（Santos, et al.,2012; Bastos, et al., 2003），如瑞娅桑塔纳（Riacho de Santana）片麻岩、混杂岩，塞特沃尔塔斯（Sete Voltas）和博阿维斯塔（Boa Vista）片麻状花岗岩及伴生的绿岩带组合。瑞娅桑塔纳混杂岩经历了3.25 Ga混合岩化作用，最小锆石U-Pb年龄为3.65 Ga，Sm-Nd模式年龄（TDM）为3.9～3.26 Ga，负的εNd(t)值（-4.7±0.3）显示其岩石有漫长的地壳演化历史。塞特沃尔塔斯TTG片麻岩常现源区原岩捕虏体，为古太古代拉斑玄武岩部分熔融的产物，含角闪石、石榴石残留矿物。灰色片麻岩（Rb-Sr等时线年龄为3.4 Ga，Sm-Nd模式年龄（TDM）为3.6～3.5 Ga）富Sr贫Yb的地球化学成分与通常的TTG不同，应该是更古老微陆块部分熔融的产物（最老锆石年龄早于4.0 Ga），可能与古陆核增生演化存在关联。博阿维斯塔为穹丘状花岗质片麻岩，成岩年龄早于3.04 Ga（Martin, et al.,1993; Nutman,1993）。

索布拉迪纽古陆核：位于SFC北区最北部，多被沙帕达迪亚曼蒂纳（Chapada Diamantina）盆地掩盖（图2）。结晶基底也是由肢解残存的绿岩带（变质火山沉积岩系）、角闪岩、混杂岩和灰色片麻岩及侵入其

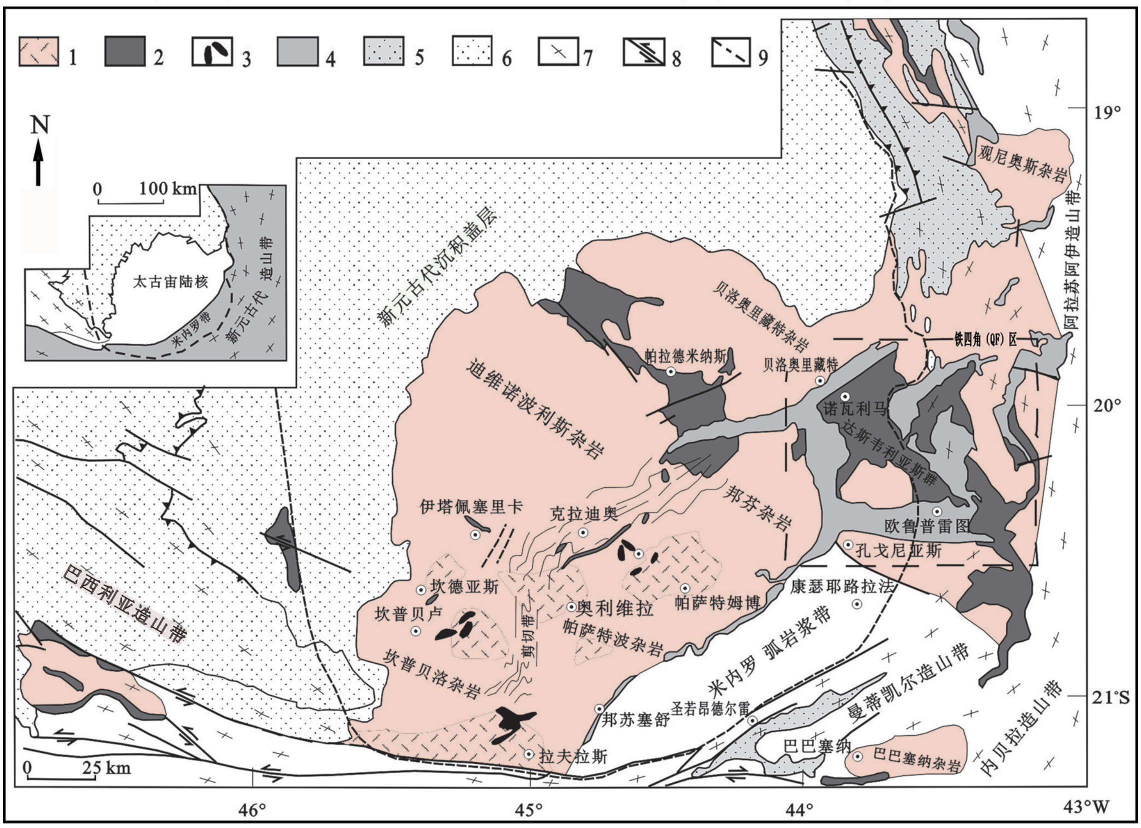

图3 圣弗朗西斯科克拉通南区地质构造略图（Wilson,2017）

Fig.3 Geologic sketch of the south segment of the São Francisco Craton

1.太古宙古陆核；2.太古宙绿岩带；3.基性–超基性岩；4.米纳斯群；5.埃斯皮尼亚索群；6.班布伊群；7.新元古代叠加改造区；8.断裂；9.SFC南部古陆核大致界线

中的花岗岩组成。片麻岩中多含辉长岩–闪长岩残余包体,其锆石年龄平均为3.5 Ga,Sm-Nd模式年龄(T_{DM})可达3.7 Ga,锆石Hf模式年龄(T_{DM})在3.9~3.7 Ga(Dantas, 2010),推测在始太古代(早于3.5 Ga)已存在古陆核。

塞里尼亚古陆核:SFC北区较小的古太古代–中太古代古陆核,主要由片麻岩,角闪岩和闪长–花岗质片麻岩、绿岩带等组成,片麻岩常含少量辉长岩–闪长岩基性残留体,锆石年龄为3.62~3.31 Ga。据Rios、Mello等人研究(Rios, et al., 2008; Mello et al., 2006),基底岩石年龄大约在3.6~2.9 Ga之间,如奥长花岗岩锆石U-Pb年龄为3.3~3.6 Ga,安布罗斯(Ambrósio)穹窿状花岗岩内有3.1 Ga混合片麻岩包体。

吉基耶古陆核:主要由麻粒岩和紫苏花岗闪长岩、花岗岩组成,岩石Sm-Nd模式年龄(TDM)在3.3~2.9 Ga,麻粒岩锆石U-Pb年龄为2.7~2.6 Ga(Barbosa, et al., 2002; Barbosa,1990; Marinho,1994a,b.),较上述3个古陆核形成略晚。

综上所述,SFC北区有早于35亿古陆壳岩石,表明在中太古代前SFC就已形成了多个古老的陆核。另外,SFC北区结晶基底顶部的雅阁比纳(Jacobina)群,形成于克拉通晚太古宙活动大陆边缘沉积盆地环境,以含金砂岩、石英岩和砾石岩为特征,而其中的碎屑岩锆石年龄可达3.5~3.2 Ga,最老的可达4.1 Ga(Wilson, 2017),同样指示古太古代之前SFC北区已形成了古陆核。

1.2 南区古陆核特征

SFC南区古陆核则由坎普贝洛(Campo Belo)、帕萨特波(Passa Tempo)、邦芬(Bonfim)和贝洛奥里藏特、迪维诺波利斯(Divinópolis)等中高级变质杂岩构成,包含(混合)灰色TTG片麻岩–花岗岩,(超)镁铁质基性火山岩和化学(碎屑)沉积岩组成的绿岩带(Rios, et al., 2009; Wilson, 2017),多分布在QF西南地区(图3)。杂岩中卡莫波利斯米纳斯(Carmópolis de Minas)群中继承性锆石$^{207}Pb/^{206}Pb$年龄为3.74 Ga,里奥达斯韦拉斯(Rio das Velhas)和米纳斯(Minas)群中的继承性锆石U-Pb年龄为3.5~3.3 Ga,部分锆石核部年龄峰值达3.81 Ga,花岗质片麻岩Sm-Nd模式年龄(TDM)在3.5~3.3 Ga(Goulart, et al., 2013; Moreira, 2016; Teixeira, et al.,2010; Goulart, 2013)。Lana等人测得QF地区片麻岩锆石核部U-Pb年龄为3.2 Ga±,在QF东部,有圣巴尔瓦拉(Santa Bárbara)穹窿片麻状花岗岩,其锆石U-Pb年龄为3.21~3.20 Ga(Lana, 2013)。综上,SFC南区古太古代就已存在了古陆核。

1.3 古陆核增生

中太古代以前,SFC古陆核经碰撞挤压作用等形成了绿岩带及环绕它们的TTG片麻岩,伴随古陆核之间的不断汇聚融熔,在高温、高压变质条件下改造出大量的长英质条(痕)带状片麻岩,同时上侵了大量的富钾花岗岩及基性–超基性岩等陆缘弧岩浆。典型的陆缘弧岩浆诸如有巴伊亚州内的伊塔布纳–萨尔瓦多–库拉萨(Itabuna-Salvador-Curaçá,以下简称"ISAC")带、米纳斯州的米内罗(Mineiro)造山带内的弧岩浆(后文阐述)。因此,这些早期的古老陆核是环绕着它们呈现不断增生的过程,这些增生造山带内的陆缘弧岩浆能使SFC古陆核稳固地拼合在一起(图4)。

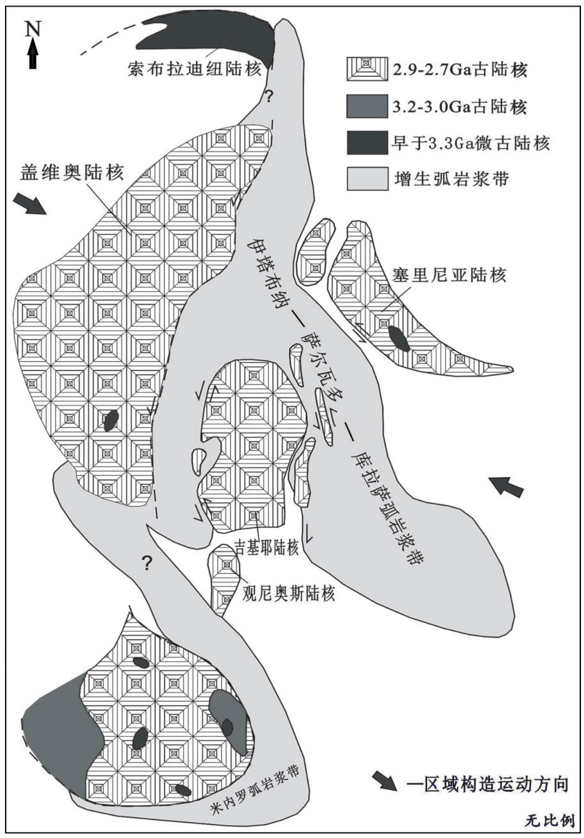

图4 圣弗朗西斯科克拉通太古宙古陆核及其增生–汇聚示意图(Wilson,2017)

Fig.4 Illustrating the relative position of Archean blocks and hyperplasia in the São Francisco Craton

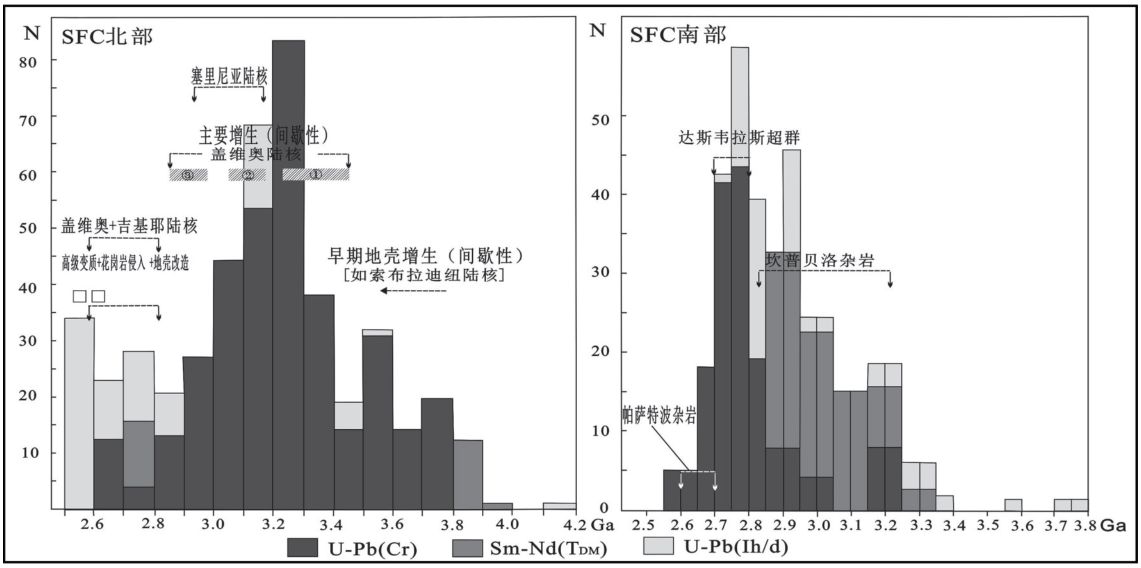

图5 圣弗朗西斯科克拉通太古宙古陆核增生期年代直方图(Bastos, et al.,2003)

Fig.5 Geochronological hisogram of Archean accretion episodes in the São Francisco Craton

Cr.岩浆锆石结晶年龄;Ih/d.继承/碎屑锆石年龄;Sm.Nd(T_{DM})模式年龄

SFC南、北区太古宙古陆核增生/分异是以TTG片麻岩穹窿和花岗岩为主。其中北区各类岩石锆石U-Pb年龄分布区间主要有:3.8~3.6 Ga;3.4~3.0 Ga;2.9~2.8 Ga;2.7~2.6 Ga,并集中于3.4~3.0 Ga,并且发现有早于4.0 Ga的碎屑锆石年龄(图5)。因此该时期是SFC古陆核大规模增生阶段,推测3.8~3.6 Ga阶段SFC以幔源玄武质岩浆底侵作用形成新生地壳(如伊比蒂拉–伊比拉萨巴(Ibitira-Ibiraçaba)片岩),且古陆核是以垂向增生为主;而2.9~2.8 Ga和2.7~2.6 Ga两期则以SFC微陆核陆陆、弧陆碰撞水平增生为主。

Lana等(2013)研究了SFC南区QF及周边TTG片麻岩、花岗岩等岩石,已获取古陆核增生年代学数据,并归纳出古陆核主要增生阶段:3.2~3.1 Ga、2.93~2.90 Ga和2.80~2.77 Ga,且主要集中在2.9~2.7 Ga阶段,表明SFC南区古陆核大规模增生作用相对北区出现较晚一些。另外有关资料显示(Moreira, 2016; Romano, et al., 1998; Teixeira, 1998; Silva, et al., 2012b):SFC南区中太古代(3.2~2.9 Ga)达斯韦利亚斯绿岩带(蕴藏世界级QF金矿)和同期钾钠质片麻状花岗岩均是在克拉通活动大陆边缘背景下形成,钙–碱性系列和拉斑系列玄武质岩浆活动则发生于早期克拉通化同–晚造山期,而中–新太古代(2.9~2.6 Ga)大规模增生以大范围富钾深熔作用为主(达斯韦拉斯造山运动引起的),且图5中的古老片麻岩–花岗岩锆石结晶年龄与Sm-Nd全岩模式年龄(T_{DM})分析,在中–新太古代古陆核增生有多旋回的弧岩浆增生特点。

2 圣弗朗西科克拉通前寒武纪重大构造事件

据前人研究(Cordani, et al., 2013a, b; Manoel, 2017; Tohver, et al., 2010; Ganade, 2014),1.78 Ga前SFC曾是游离哥伦比亚(Columbia, 2.1~1.3 Ga)超大陆之外"中非块体"(Central African Block)的一部分,"中非块体"则是由SFC与刚果(Congo)、拉普拉塔(Rio de la Plata)、喀拉哈里(Kalahari)等地块组成(图1a),而古元古代1.78 Ga前的古地磁数据非常有限,因此无法追溯在此前块体的漂移轨迹,它们的拼合/聚合地质构造事件仅以岩石组合特征及地质年代学数据而加以推断。Manoel等(2017)研究又证实了1.78~0.98 Ga间SFC没有和罗迪尼亚(Rodinia, 1.3~0.75 Ga)大陆发生碰撞拼合,而是伴随"中非块体"在1.0 Ga前从北半球低纬度向高纬度顺时针旋转和漂移,并经历"冷冻"雪球事件,才渐与哥伦比亚大陆解体出来的亚马逊、西非等克拉通发生碰撞(0.79~0.61 Ga),其他块体(如南极洲、澳大利亚和印度等)也陆续与"中非块体"发生碰撞拼合/聚合(形成巴西利亚/泛非事件0.64~0.50 Ga)而形成冈瓦纳古陆(图6)。

本文据SFC在全球板块构造背景结合已发表的文献等资料(Cordani, et al.,2013a,b; Manoel,2017; Tohver, et al.,2010; Ganade,2014),将其前寒武纪重大构造演化事件归纳相应划分为太古宙古陆核形成-碰撞拼合、古元古代弧岩浆活动、中元古代-新元古代早期陆内盆地裂谷与基底隆升、新元古代边缘性造山带等4期重要的地质演化过程,详细如下:

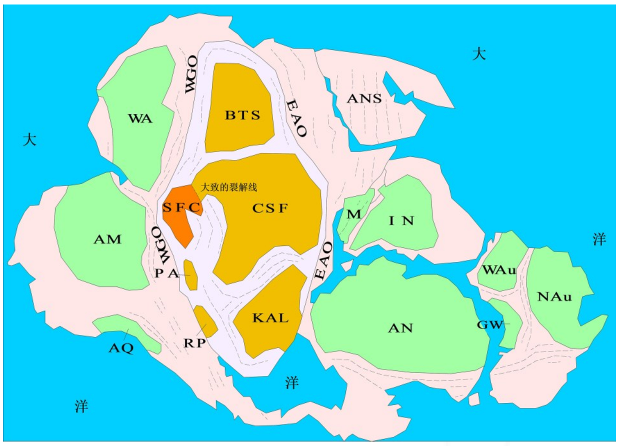

图6 冈瓦纳古陆拼合构造略图(据Manoel,2017略改)

Fig.6 Gondwana cofiguration adapted with some modfications

CSF.冈果-圣弗朗斯西科地块(含SFC);KAL.喀拉哈里地块;PA.巴拉那帕内玛地块;RP.拉普拉塔地块;WA.西非克拉通; AM.亚马逊克拉通;AQ.阿雷基帕地块;BTS.博尔博雷马-跨撒哈拉地块;M.马达加斯加地块;IN.印度地块;AN.南极洲地块; Wau.西澳大利亚地块;Nau.北澳大利亚地块;GW.高勒地块;EAO-东非造山带;WGO.西冈瓦纳造山带;ANS.阿拉伯-努比亚地块

2.1 太古宙古陆核碰撞拼合

在中太古代坎波贝洛造山运动(Campo Below Orogeny,3.05 ~ 2.92 Ga)(Lana, 2013)、新太古代达斯韦拉斯(2.79 ~ 2.75 Ga 和 2.73 ~ 2.7 Ga)(Machado, 1992)等多期次的挤压、伸展造山构造作用下(图4),SFC南区岩石地层发生不同程度的变质、变形改造而难以识别矿物组分; SFC北区在新太古代则受到多个微陆块强烈碰撞而发生强烈地叠加发生了高级变质、变形改造作用,使其残存的古陆核多呈现高温变质麻粒岩相岩石,矿物组分主要为紫苏辉石(或古铜辉石)、透辉石(或次透辉石)、铁镁铝榴石、堇青石、矽线石(或蓝晶石)、条纹长石、斜长石等无水变质矿物为主。

太古宙SFC各个古陆核碰撞拼合/聚合界线常以花岗岩类-绿岩带为识别标志。在巴伊亚和米纳斯吉拉斯州内的绿岩带形成于中、新太古代(3.2 ~ 2.9 Ga,2.86 ~ 2.5 Ga),包括科马提岩、变质玄武岩和变质安山岩、BIF条带状硅铁建造夹硅质岩(表1)。SFC南区分布有皮乌姆希(Piumhi)、福塔莱萨-莫罗(Fortaleza de Minas-Morro do Ferro)、巴巴塞纳(Barbacena)等绿岩带;北区分布蒙多诺沃(Mundo Novo)、拉戈阿德阿雷格里(Lagoa do Alegre)、布鲁马杜(Bru-

表1 圣弗朗西斯科克拉通中-新太古代绿岩带年代及地质特征

Table 1 Geologic-geochronologic characteristics of neo-meoarchean greenstone belt in the São Francisco Craton

SFC绿岩带		主要地质特征	测试方法	年龄 / Ga	构造环境	参考文献
南区	皮乌姆希	镁铁质-超镁铁质岩,火山碎屑岩,化学沉积岩被长英质次火山岩侵入	锆石 U-Pb	3.0 ~ 3.12	基底隆升,地壳伸展挤压	Alkmim,1998
	福塔莱萨-莫罗	残余科马提岩、碎屑沉积岩、凝灰岩	Sm-Nd Rb-Sr	2.86 2.92	基底韧性构造变形	Alkmim,1998; Lobato, 2007
	巴巴塞纳	镁铁质-超镁铁质(科玛提岩)和变质岩	Sm-Nd 、Rb-Sr 锆石 U-Pb	3.19 ~ 3.22 2.97	TTG侵入	Moreira, 2016
北区	蒙多诺沃	下层为滑石、绿泥片岩、蛇纹岩、角闪岩等;中层为枕状玄武岩,英安岩、流纹岩、熔结凝灰岩等伴随炭质片岩夹条带状硅铁建造;上层为石英片岩、千枚岩、石英岩和砾岩等	锆石 U-Pb	3.31	古洋壳和岛弧岩浆增生	Peucat, 2002
	拉戈阿德阿雷格里	下层为BIF条带状硅铁建造和滑石片岩、透闪石片岩等;上层为片麻岩、石英岩含蓝晶石片岩和条带状硅铁建造等	花岗岩最小年龄	>3.3	基底断裂构造	Bastos, et al., 2003
	布鲁马杜	下层为科马提岩和玄武岩夹燧石、条带状硅铁建造和石英岩;中层为黑云母片岩;上层白云岩、条带状硅铁建造和石英岩	锆石 U-Pb	2.74	TTG侵入	Santos, et al., 2012; Bastos, et al., 2003
	博基拉	下层为科马提岩组成;中层为玄武岩;上层为石英燧石、BIF条带状硅铁建造夹硅质岩	方铅矿 Pb-Pb	2.5 ~ 2.7	基底片麻理化、混合岩化作用	Bastos, et al., 2003; Nutman, 1993

mado)、博基拉(Boquira)等绿岩带(Ezequiel,2019; Nutman,1993; Paquette,2015; Lana, et al., 2013; Farina, et al., 2015)。这些绿岩带形成皆早于2.5 Ga,多分布于克拉通古陆核边缘(图1c)。已有的资料证明(Teixeira,1991; Lana, et al., 2013; Farina, 2015; Teixeira,2017):大约在太古宙2.8~2.7 Ga期间的古陆核碰撞发生的岩浆-构造演化常包括多期次TTG弧岩浆增生/结晶分异和岩浆深熔混合岩化作用,并在新太古代晚期(2.5 Ga±)与刚果古陆块形成连贯陆块。SFC微古陆核拼合形成稳定的太古宙古陆核,在巴西也称之为“帕拉米林克拉通”(Almeida,1981)。

2.2 古元古代弧岩浆带

受古元古代2.1~2.0 Ga泛亚马逊造山事件影响(Cahen, et al.,1984; Teixeira,1991),SFC北区弧岩浆多集中于巴西巴伊亚州中东部较大规模ISAC造山带内(图1c),并形成近南北向JCML构造带和区域变形变质作用(Teixeira,1991; Ernst, et al.,2013; Pierre,1990);SFC南区弧岩浆则集中于米纳斯吉拉斯州米内罗造山带弧岩浆,形成了米内罗/曼蒂凯尔造山带及其变质、变形弧岩浆区(图3)。古元古代(约2.0~1.9 Ga)造山运动形成的弧岩浆代表了SFC早期裂解的岩浆记录,是中元古代陆内裂谷与基底隆升初始的具体体现。

2.2.1 圣弗朗西斯科北区ISAC弧岩浆活动带

SFC北区ISAC弧岩浆带长约800 km,呈南北向展布(图1c,图4),且从太古宙晚期开始至古元古代一直持续活动,形成于SFC古陆核边缘,它们部分肢解了SFC北区基底和古元古代早期火山岩地层(Barbosa, et al.,2002; Barbosa, 2002),上侵的长英质岩浆主要是拉斑玄武岩质洋壳融熔的产物,并以含石榴石石英岩、锰、铝-镁质片麻岩原岩和2.6 Ga变形紫苏花岗岩、麻粒岩及富含蓝宝石、石墨等岩石矿物为显著特征(Peucat, et al., 2011)。ISAC岩浆记录了SFC古陆核碰撞前、同碰撞的弧岩浆演化阶段:碰撞前为2.3~2.1 Ga钙碱性玄武岩和富钾-过铝质花岗岩和二长花岗岩;2.16~2.11 Ga钙碱性-过铝质TTG普遍侵入北区的南部基底或里奥伊塔皮库鲁(Rio-Itapicuru)火山沉积岩层中(Chauve,1997);同-晚期碰撞期2.1~2.06 Ga弧岩浆带内则形成钠质、碱性正长岩和白云母花岗岩(Oliveira, 2004b)。

2.2.2 圣弗朗西斯科南区米内罗弧岩浆活动带

SFC南区米内罗弧岩浆带主要位于米纳斯吉拉斯州南部地区(图3,4),呈NE向长约180 km(Teixeira,1991),活动带多被认为是大洋内弧系统和大陆边缘盆地,其岩石单元由不同类型正片麻岩类(TTG、花岗岩)、未变形火成岩(辉长岩)等组成,且侵入古元古代晚期弱碱性A型花岗岩,发育大量铌钽伟晶岩脉群。该活动带在2.5~2.4 Ga形成成铁纪米纳斯半封闭洋盆,发育了QF区富金的达斯韦利亚斯群,且蕴藏了世界古老且重要的BIF矿床(2.5 Ga±)(Machado, 1992; Barbosa, 2015; Moreira, 2016),在古元古代(2.35~2.12 Ga)成铁纪米纳斯洋发生闭合转变为弧后区/前陆沉积中心,形成米纳斯群、伊塔科洛米(Itacolomi)群,并在2.1~2.0 Ga以伊塔科洛米群砂砾岩沉积相而结束(Ávila, 2014; Teixeira, 2015)。

2.3 古元古代晚期-新元古代早期陆内裂谷与基底隆升阶段

太古宙晚期-古元古代以前,SFC与非洲刚果克拉通联为一体,古元古代晚期-新元古代早期进入拉张伸展构造为主的克拉通演化阶段(1.78~1.20 Ga),产生了埃斯皮尼亚索(Espinhaço)等裂谷(陷)和陆内非造山型岩浆活动,同时上侵了大量基性岩墙群。

SFC古元古代晚期陆内非造山型岩浆是以Fe/(Fe+Mg)值、K_2O/Na_2O值和K_2O含量较高,而CaO、Al_2O_3含量较低为特征的富硅、碱,贫钙、镁、铝的弱碱性A型花岗岩为主,时代主要集中在1.7 Ga左右,典型的非造山型岩浆形成米纳斯吉纳斯州南部的博拉丘多斯(Borrachudos)岩体。

SFC陆内拉张伸展构造事件伴生基性岩墙群产出,按年龄分为两类(表2):一类为太古宙-古元古代瓦奥阿(Uauá)、拉夫拉斯(Lavras)和帕罗佩巴(Paraopeba)等岩墙群,代表了SFC初始的地幔耦合克拉通化过程;古元古代晚期-新元古代岩墙群包括帕拉德米纳斯(Pará de Minas)、库拉萨(Curaçá)、迪亚曼蒂纳-帕罗米林(Diamantina-Paramirim)、奥利文萨(Olivença)-萨尔瓦多(Salvador)等,它们则记录了SFC伸展-拉张为裂谷或断陷盆地等陆内裂解过程。在SFC北区基性岩墙群总体呈NE-SW走向,多侵入克拉通中高级片麻岩中(Oliveira, 2012; Bastos, 1994; Silveira, 2013; Alkmim, 2006; Girardi, 2013);

表2 圣弗朗西斯科克拉通基性岩墙群时、空分布及地质构造特征

Table 2 Geologic tectonics characteristics for mafic dyke of the São Francisco Craton, in Space and Time

基性岩墙群		主要岩性	测试方法	年龄 / Ga	位置及构造环境（主要产状）	参考文献
新元古代–中元古代	萨尔瓦多–奥利文萨	辉绿岩	U-Pb(斜锆石)	0.92	北部,陆内板块（NS,NE-SW,EW）	Oliveira, 2012
	迪亚曼蒂纳	(变)辉绿岩 角闪岩	U-Pb(斜锆石)	0.93	南部,陆内板块（EW ,NW,NS,NE）	Teixeira, 2015
	迪亚曼蒂纳–帕罗米林	辉绿岩,玄武岩	U-Pb(斜锆石)	1.50	北部,陆内板块（NNW-SSE）	Bastos, 1994
	库拉萨	玄武岩	U-Pb(斜锆石)	1.50	北部,陆内板块（NE）	Bastos, 1994
古元代–新太古代	帕拉德米纳斯	辉绿岩	U-Pb(斜锆石)	1.71	南部,陆内双峰式火山区（NW）	Moreira, 2016
	拉夫拉斯	角闪岩,(变)辉绿岩	Ar-Ar(角闪石)	1.97	南部,挤压/剪切（NE,NS）	Goulart, et al.,2013; Goulart,2013
		苏长岩	全岩Sm-Nd等时线	2.66	南部,衰亡裂谷（NW）	Goulart, et al.,2013; Goulart,2013
	帕罗佩巴	(变)辉绿岩 角闪岩	全岩Rb-Sr等时线	2.10 ~ 2.19	南部,挤压/剪切带（NNW,NS）	Teixeira, et al., 2010; Teixeira, 1998
	瓦奥阿	苏长岩,角闪岩,(变)辉绿岩	U-Pb(锆石)	2.62 ~ 2.73	北部,晚–后造山运动（NW-SE,NS）	Oliveira, 2012, Bastos, 1994

而南区岩墙群总体走向呈NE-SW或N-S向,多侵入花岗岩中。南、北区元古宙基性岩墙年龄峰值多数集中于1.71 Ga,且与埃斯皮尼亚索裂谷系形成大致吻合(Teixeira, et al.,2010; Guadagnin,2015; Girardi, 2017),这些基性岩墙对分析SFC岩石圈破裂岩石成因过程,推断地幔源组分具有重要意义。

2.4 新元古代克拉通边缘造山带

除东部大西洋沿岸外,SFC被新元古代里奥普雷图和塞尔吉帕诺、巴西利亚、里贝拉、阿拉苏阿伊等造山带环绕围限(图1c)。这些造山带主要在埃迪卡拉纪巴西利亚/泛非运动过程中逐渐形成,部分受SFC与亚马逊、西非等古陆核汇聚融合的影响,共同参与了前寒武晚期SFC的地质演化过程。

北部里奥普雷图、塞尔吉帕诺造山带整个造山活动从新元古代早期(0.90~0.82 Ga)开始,沿SFC北部边缘近东西向延伸达1 000 km以上(Caxito, 2014a)。

里奥普雷图造山带基底由太古代紫苏花岗岩–花岗闪长岩、奥长花岗岩、紫苏花岗闪长–奥长花岗质片麻岩,辉长–苏长岩等组成。出露古元古代中晚期(1.9 Ga)福尔摩沙(Formosa)组和新元古代班布伊(Bambuí)群,且发育新元古代流纹英安岩、流纹岩、凝灰岩等酸性火山岩及石英岩、钙–硅质大理岩等变质岩系,并多被新元古代同碰撞–碰撞后非造山型弱碱性花岗岩侵入(Caxito, 2014b,c,d, 2015; Trompette, 2000)。

塞尔吉帕诺造山带为“西非克拉通”乌班吉德(Oubanguide)造山带西延的部分,是新元古代多期次逆冲到SFC北部边缘的增生体。带内出露花岗闪长岩、花岗岩等深成岩、喷发火山沉积岩和强变形剪切作用形成的榴辉岩相白云母片岩等变质沉积岩系(Caxito, 2016)。

西部巴西利亚造山带沿SFC西部边缘绵延长约1 200 km,开始于新元古代拉伸纪(0.90 Ga)SFC裂谷晚期,终止于新元古代晚期(0.54 Ga)SFC与巴拉那帕内玛(Paranapanema)、戈亚斯(Goias)等古微陆核汇聚碰撞阶段。造山带基底为蛇绿混杂岩、戈亚斯、马拉罗莎(Mara Rosa)增生弧岩浆岩及伴生的辉长岩–闪长岩等火成岩组合(Pimentel, 1992),应是巴拉那帕内玛、戈亚斯等古陆核与SFC汇聚/拼合的产物。

南部里贝拉造山带 呈北东向延长,是0.64~0.62 Ga西刚果古陆块与SFC南缘汇聚碰撞的产物,产生了大量I、S型弧岩浆和逆掩构造体系,多被杂岩、硅质碎屑岩、碳酸盐岩地层覆盖(Laux, 2005; Heilbron, 2008; Monica, 2017; Trouw, 2013)。

东南部阿拉苏阿伊造山带始于埃迪卡拉纪早期，为SFC较晚期造山带，并且是阿达玛斯特（Adamastor）洋闭合产物。该带出露拉伸-埃迪卡拉纪沉积的马考巴斯（Macaúbas）群、埃斯皮尼亚索群，侵入的花岗岩等火成岩记录了0.63～0.59 Ga、0.59～0.56 Ga、0.56～0.53 Ga等多期次岩浆演化过程（Pedrosa, 2001, 2008; Alkmim, 2006）。

3 圣弗朗西斯科克拉通化形成过程

所谓克拉通化是壳幔耦合使其形成稳定上、下地壳圈层的过程。地球上所有克拉通化和克拉通都形成于寒武拉伸纪（早于1.0 Ga）前，且80%以上克拉通古陆核在2.5 Ga前就已形成，普遍经历了多期次的克拉通化过程（李永华等，2011）。大陆克拉通化能够避免遭受后期地幔物质对流侵蚀、板块俯冲等影响而长期稳定地存在，并为显生宙岩石圈沉积–构造演化奠定了稳定的岩石单元基础（Zhai, 2000a, b; Kusky, 1990; Cruz, 1997; Nutman, 1993; Santos, 2012）。巴西圣弗朗西斯科克拉通同样经历了多期、复杂的克拉通形成过程。

3.1 太古宙初始克拉通化

早期SFC是由太古宙盖维奥等较小微陆块（核）碰撞汇聚/拼合而成，克拉通拼贴缝合带是以绿岩带–花岗岩类为标志。如SFC北部盖维奥、塞里尼亚和吉基埃古陆核经蒙多诺沃、拉戈阿德阿雷格里、布鲁马多等绿岩带焊接、聚合而成（表1），并经历3期岩浆深熔作用（Santos, 2012; Leite, 2009; Alkmim, 2012）：古太古代（3.6～3.3 Ga）以拉瓜塔伊（Caraguataí）为代表的碱性花岗岩、正长岩和石英正长岩组成的富钠质碱性TTG岩系，形成早期的克拉通化；以中太古代（3.2～2.9 Ga）钾–钠质花岗岩侵入为标志的克拉通化；以中–新太古代（2.9～2.6 Ga）大范围的钾质花岗岩形成为标志的克拉通化，具有弧–弧、弧–陆或陆–陆拼合的特点，另有钙–碱性弧型花岗岩、同碰撞混合岩等岩石。因此早期SFC古陆核经碰撞形成绿岩带围绕并使之连成整体，钠、钾质弧岩浆活动使古陆核稳固加厚（图4），之后发生变质作用、陆内花岗岩及瓦奥阿等基性岩墙群的壳幔耦合，标志着SFC微古陆核拼贴完成，形成太古宙克拉通化（陆核体）雏形。

3.2 古元古代变质作用及新元古代终极克拉通化

2.08～2.04 Ga发生的泛亚马逊造山运动使SFC太古代基底普遍发生区域变质作用，如巴伊亚州帕拉米林裂陷区和米纳斯吉拉斯州沙帕达迪亚曼蒂纳盆地裂陷区出露的岩石都已发生不同程度区域变质、变形作用（Alkmim, 2012; Chemale, 2012）。SFC在经历古元古代晚期变质事件后，伴随中–新元古代陆内伸展和拉张过程，上侵了诸如库拉萨等众多基性岩墙群及伴生喷发长英质陆相火山岩浆，这些基性岩墙群及陆内非造山型岩浆参与SFC地幔耦合过程，是完成SFC最终克拉通化的显著标志。

4 圣弗朗西斯科前寒武纪重要成矿作用

SFC前寒武纪成矿作用是克拉通地质构造演化的产物。圣弗朗西斯科前寒武纪重大地质构造演化事件（表3）制约造就了SFC成矿活动，且在克拉通内呈有规律、有序的分布，呈现完好的地质记录（图7）。本文据前文克拉通内重大构造事件对SFC划出4期重要成矿期，矿产有金、金刚石、铁、铅、锌、铀、锰、铌钽及磷矿等数十种，其中多数金属矿与前寒武纪地质事件相关，涉及的矿床类型主要有绿岩型金矿、苏必利尔湖型BIF型铁矿、基性–超基性岩型镍铜硫化物矿、VMS型铜矿、SEDEX型铅–锌矿、海相沉积铁锰、磷矿、金刚石及砂金、金刚石砂矿等。

4.1 太古宙陆核碰撞拼合成矿期（2.5 Ga前）

太古宙前成矿期主要与SFC盖维奥等古陆核碰撞、拼合产生的绿岩带及太古宙洋壳、岛弧增生等演化事件关联，成矿作用表现为大规模酸性岩浆侵入并伴随超–中基性火山喷发沉积物，形成众多花岗岩基和绿岩带，而矿床多产在与变质火山–沉积岩绿岩带内，有两套成矿系列：一套为变质火山–沉积岩系内的绿岩型金矿、BIF铁矿和SEDEX型铅锌矿。另一套为镁铁质、超镁铁质杂岩体（科马提岩）内有铜矿和镍铬钒矿等矿产，一般成矿规模较小。绿岩型金矿床常在绿岩带内呈带状或不规则状分布，代表性的有位于米纳斯吉拉斯（Minas Gerais）州府贝洛奥里藏特东南12 km的莫罗韦洛（Morro Velho）矿床，矿床矿石中独居石SHRIMP U-Pb年龄为2.67 Ga，成矿与太古代古陆块洋壳俯冲、岛弧增生形成的超镁

表3 圣弗朗西斯科克拉通前寒武纪大规模重要成矿事件

Table 3 Massive major mineralization in the Precambrian of the São Francisco Craton

重大构造事件	地质构造背景	主要成矿期	主要矿床类型	典型矿床
冈瓦纳泛大陆拼合 巴西利亚/泛非造山运动事件 最终克拉通化	上侵基性岩墙群,非造造山型岩浆活动,活动陆缘盆地沉积、边缘造山带	新元古代 (1.0 ~ 0.54 Ga)	海相沉积铁锰、磷矿,砂锡矿,伟晶岩型铌钽矿,金刚石矿床及砂金矿,金刚石砂矿等	博尔博雷玛伟晶岩型铌钽矿,巴雷拉斯锰矿,伊列斯(Irecê)磷矿
裂谷盆地 非造山岩浆活动 基底抬升与拉张事件	大规模裂谷系和非造山型构造岩浆活动,上侵基性岩墙群,双峰式陆相火山活动及盆地沉积作用	古元古代固结纪-中元古代 (1.8 ~ 1.0 Ga)	VMS型铅-锌矿、铬钒钛铁磷矿、铜矿、稀土矿、铀金矿、砂金矿等	拉戈阿雷亚尔铀矿床,沙帕达迪亚曼蒂纳金刚石砂矿
泛亚马逊造山事件 弧岩浆作用 初始克拉通化	弧岩浆活动带,活动大陆边缘半封闭洋盆沉积作用、地幔上涌侵入众多基性岩墙。活动大陆边缘钙碱性岩浆作用	古元古代早中期 (2.5 ~ 1.8 Ga)	苏必利尔湖型BIF铁矿,VMS型Pb-Zn矿,IOCG铜金矿等	阿拉西金矿,科奎罗锌矿,拉夫拉韦利亚IOCG矿,雅阁比纳铀金矿
先挤压后伸展运动(达斯韦拉斯等构造运动) 古陆核碰撞融合事件	古陆核边缘,古地壳形成与增生,绿岩带或高级变质变形作用,活动古大陆边缘剥蚀沉积	太古宙 (早于2.5 Ga)	绿岩型金矿,含金-铀砾岩型矿,苏必利尔湖型BIF铁矿,SEDEX型铅锌-铜矿,VMS型铜矿等	莫罗韦洛金矿,博基拉铅锌矿,卡拉伊巴铜矿

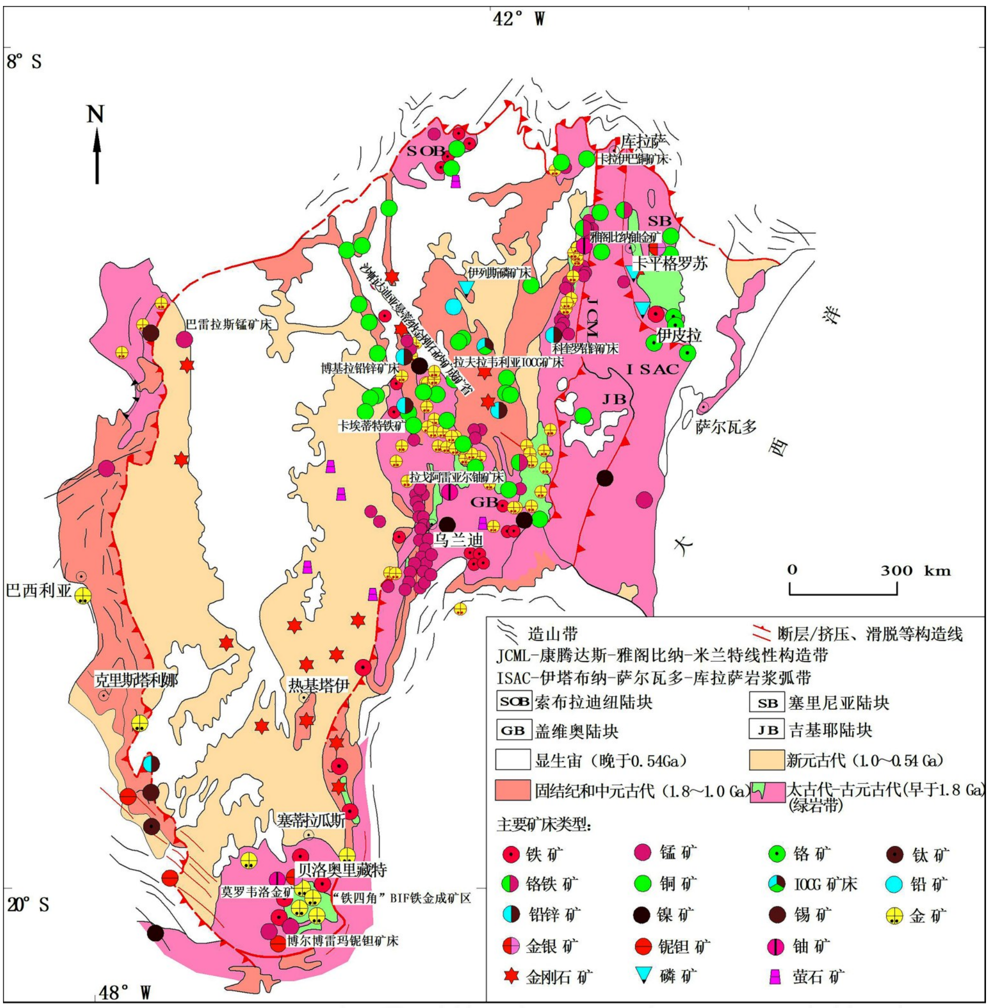

图7 圣弗朗西斯科克拉通前寒武纪大规模主要成矿作用矿产分布

Fig.7 Distribution of major deposit for massive mineralization before Precambrian of São Francisco Craton

铁质岩浆有关(Lobato, 2007);而BIF铁矿为苏必利尔湖型铁矿床,主要分布于SFC"铁四角"区伊塔比腊(Tabira)群主要含矿层内,矿石矿物以磁铁矿为主,假象赤铁矿次之,次生矿物有褐铁矿等,富铁品位一般超过60%以上,且富含金矿,新太古代是其重要的成矿期,总体成矿时代略早于我国华北密云–冀东、五台–吕梁地区变质型(沉积变质型)BIF铁矿(李俊建等,2002)。铜矿床则主要分布在SFC北部巴伊亚州内,成因与SFC古陆块碰撞、拼合过程产生的镁铁质–超镁铁质基性岩体(科马提岩)相关,典型的为卡拉伊巴(Caraíba)铜矿床, Cu平均品位 1.82%,可能为新太古代VMS型矿床变异形成的。而典型的SEDEX型铅锌矿床有博基拉(Boquira)铅锌矿床,Pb-Zn品位2%~9%,成矿锆石 U-Pb年龄为2.7~2.5 Ga,是SFC太古宙现存少有的SEDEX型铅锌矿床,形成于克拉通拉张–伸展的构造环境(徐鸣等,2017)。

4.2 古元古代早中泛亚马逊造山运动成矿期(2.5~1.8 Ga)

古元古代成矿系列主要是泛亚马逊造山旋回作用影响产物,与SFC微陆块弧岩浆带演化或洋盆闭合沉积成矿作用密切相关。此阶段岩浆各类丰富,岩石组合最多,岩浆作用强烈,成矿作用最强烈,大致形成四套成矿系列:一套为变质火山–沉积岩相关的绿岩金矿床、古火山型、斑岩型Cu-Co-Ni矿床,VMS型含银Zn-Pb多金属矿床、菱铁矿等矿床系列;第二套为变质铁镁质、超镁铁质杂岩体相关的铬铁矿–镍钴矿床;第三套为辉长岩–斜长岩体相关的钛钒矿或氧化铁–铜–金(Iron Oxide-Copper-Gold,简称"IOCG")矿床等;第四套米那斯超群含铁石英岩系相关的造山型金矿床或变质石英砾岩型铀、金系列矿床,多数金矿体受断裂控制。代表性氧化铁–铜–金(IOCG)矿床有巴伊亚州赋存于伊比蒂亚拉(Ibitiara)富铁–钙质角砾岩中的拉夫拉韦利亚(Lavra Velha)矿床,成矿时代为古–中元古代(2.1 Ga±),Au品位4.29 g/t ,Cu品位高达8%,伴生LREE、U、Co等元素,钙质角砾、方解石中碳、氧同位素为$\delta^{13}C$为~2 ‰和$\delta^{18}O$为9.95‰~13.09‰,黄铜矿、黄铁矿中硫同位素$\delta^{34}S$为2.22‰~3.89‰,说明成矿流体同位素来源多样混合,是幔源基性、碱性岩浆源区热液成矿流体形成的IOCG矿床(Leandro, et al.,2020)。巴伊亚中北部瑟林那–瓦瓦绿岩带中阿拉西(Araci)金矿床,平均品位7 g/t,成矿时代(白云母Ar-Ar定年2.05 Ga)较绿岩带形成(2.2~2.1 Ga)略晚,表明先后继承性成矿关系;雅阁比纳铀–金矿床主要赋存于雅科比纳群含镁铁质和超镁铁质岩的石英岩和变质砾岩夹层中,金平均品位4 g/t,成矿时代为1.94~1.91 Ga(白云母Ar-Ar年龄)(Teixeira, et al., 2010)。VMS铅锌矿床有代表性的科奎罗(Fazenda Coqueiro)铅锌矿床,矿床受盖维奥古陆块边缘钙碱性火山岩控制,铅锌平均品位6.2%,形成时代2.15~1.95 Ga(锆石 U-Pb),铅锌矿化与SFC弧后裂谷盆地火山沉积作用相关(Spreafico, et al., 2019)。

4.3 古元古代固结纪–中元古代陆内裂谷与基底隆升成矿期(1.8~1.0 Ga)

古元古代固结纪–中元古代成矿作用主要受SFC基底抬升与拉张,裂谷盆地构造演化产生的非造山碱性–弱碱性火山杂岩(A型花岗岩)、基性岩等岩浆控制。常形成与超基性侵入岩有关的铬、钒、镍、铜等矿床,非造山岩浆作用有关的稀土矿、铀等系列矿床。代表性的矿床有巴伊亚州卡埃蒂特市的拉戈阿雷亚尔(Lagoa Real)铀矿床,矿床赋存于帕拉米林裂陷槽中拉戈阿雷亚尔富钾钠片麻岩等杂岩内,包括38个铀异常区,面积达1 200 km^2,铀矿化多与高Sr初始比值的壳源型花岗岩碱交代作用密切相关,且以斜长石+钠长石–铀共生矿化矿物组合为特征,U_3O_8矿石品位0.12%~0.27%,总储量达11.2万吨(Lucas, et al., 2021; Lydia, 2015)。

4.4 新元古代巴西利亚/泛非造山运动成矿期(1.0~0.54 Ga)

新元古代SFC参与了冈瓦纳泛大陆拼合,巴西利亚/泛非运动使其边缘发生系列造山沉积改造成矿作用,形成了铁、锰–金刚石–铌钽矿–金矿和非金属矿床系列,如碱性花岗岩(伟晶)型铌钽矿床,沉积改造表生作用形成的铁锰矿,砂锡矿,砂铜矿及砂金矿等矿床,与陆缘–浅海沉积相关的锰矿及磷块岩、硬石膏矿等非金属矿床。该时期形成的似层状锰矿床多沿SFC古地形隆起不连续沉积分布,且与片岩、大理岩、钙硅酸盐岩伴生产出。典型的巴雷拉斯(Barreiras)锰矿床,呈北西–南东向延伸约350 km,由近40多个小锰矿体组成,多赋存新元古代上部地层。卡埃

蒂特–利西尼奥德阿尔梅达(Licínio de Almeida)–乌兰迪(Urandi)一线(图7)也分布众多的中小型铁锰矿,矿床多沿盖维奥地块瓜纳比–科伦蒂娜(Guanambi-Correntina)古老结晶基底地形分布,锰品位多为20%~50%,总储量可达12.34×10^6吨以上。而铌钽矿床多为复合型伟晶岩锂–铌–钽矿床,主要分布在米纳斯吉那斯州南部的伊坦贝(Itambé)、阿拉苏伊(Araçuaí)、新埃拉(Nova Era)等矿集区内,代表性的有塔皮拉(Tapira)、黑塞拉利昂(Serra Negra)、圣若昂德尔雷(São Joao del Rei)等矿床,铌钽成矿作用与大量S型钙碱性花岗岩相关,铌钽矿多富集在岩体上部的白云母化花岗伟晶岩脉内,以稀有金属Li-Rb-Cs-Be-Hf等元素为特征,构成岩浆气液分异的伟晶岩型铌钽成矿模式(Lucas, et al., 2021; 沈莽庭等,2021; 熊定一等,2023)。金刚石砂矿主要分布在沙帕达迪亚曼蒂纳矿集区内,呈NW-SE向超过300 km展布,金刚石砂矿主要赋存埃斯皮尼亚索群内风化剥蚀形成的砾岩层内。SFC北区原生金刚石矿床主要分布在塞里尼亚地块中部布拉乌纳(Braúna)成矿省内透辉石–金云母金伯利岩内,多呈NW向线状展布(Pizani, et al., 2001; Donatti, 2008)。

SFC新元古代磷矿床多分布在巴伊亚州内伊列斯(Irecê)盆地内或卡平格罗苏–伊皮拉(Capim Grosso-Ipirá)近南北向展布的成矿带内。代表性有伊列斯(Irecê)磷矿床,位于乌纳(Una)群白云岩层中,以碳氟磷灰石($Ca_5(PO_4)_3F$)矿石矿物为主,是SFC盆地边缘浅海潮下–潮间带沉积环境形成的典型矿床。

5 结论

(1)巴西圣弗朗西斯科克拉通有大于4.0 Ga漫长复杂演化过程:3.5 Ga前是由北区的太古宙盖维奥、索布拉迪纽、塞里尼亚和吉基耶等4个微古陆核及南区古陆核经相互碰撞、拼合后增生而形成的稳定(微)古陆核的;3.3~2.9 Ga和2.8~2.5 Ga古陆核发育绿岩带–增生岩浆造山带;古元古代(2.3~1.9 Ga)泛亚马逊造山带弧岩浆作用和1.78~1.20 Ga基底隆升和裂谷等改造演化形成了大量基性岩墙群及陆内非造山型岩浆岩;新元古代环绕克拉通边缘形成6个活动造山带。

(2)圣弗朗西斯科克拉通演化过程中形成4期重要成矿作用。即太古宙(2.5 Ga前)形成绿岩型金矿、苏必利尔湖型硅铁建造为主的变质火山–沉积等矿床成矿系列;古元古代早中期(2.5~1.8 Ga)形成与(超)基性岩相关的铜镍钴硫化物矿床、VMS型铅锌银矿床、IOCG等矿床成矿系列;固结纪–中元古代(1.8~1.0 Ga)形成与陆内(缘)裂谷相关的钒–钛–铁矿床,与非造山岩浆作用相关的铌钽矿、铀矿等矿床成矿系列;新元古代(1.0~0.54 Ga)形成铁锰、砂锡矿和磷矿等非金属矿床为主的成矿系列,包括与古陆缘–浅海沉积环境有关的(冲积)金刚石砂矿等矿床。

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