

## Chapter 2

# The Late Archaean Uauá Mafic Dyke Swarm, São Francisco Craton, Brazil, and Implications for Palaeoproterozoic Extrusion Tectonics and Orogen Reconstruction

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### Introduction

Cratons and Precambrian orogenic belts are key geological sites to help understand how the continental crust grows and how the continents assemble and break up. Mafic dykes play an important role in these tectonic studies because they may form dyke swarms that emplace parallel to a continental margin, or form radiating swarms branching out from a common magmatic centre where continental breakup may ultimately take place. As such they are useful geological records for supercontinent reconstruction (e.g. Ernst and Buchan, 1997; Wingate and Gidding, 2000; Pesonen et al., 2003; Gladkochub et al., 2010; French and Heaman, 2010) and breakup (e.g. Corrêa Gomes and Oliveira, 2000; Shellnutt et al., 2004; Mason and Brewer, 2004; Kullerud et al., 2006). Some dyke swarms remain undeformed in the craton/continent interior as the failed arm of a rift and in this circumstance they may preserve magma flow indicators that help infer the potential locus of magma propagation with associated basalts and layered mafic-ultramafic complexes (e.g. Gibson et al., 1987; Maurice et al., 2009; Klausen et al., 2010).

Mafic dykes are a major component of the São Francisco Craton in Brazil (Sial et al., 1987; Corrêa Gomes and Oliveira, 2000) but their ages and tectonic significance are poorly constrained. Of particular interest are the Palaeoproterozoic (or older) dyke swarms in the northeastern part of the craton, which are related to the evolution of the Archaean-Palaeoproterozoic Itabuna-Salvador-Curaçá orogen. This orogen is the result of Palaeoproterozoic collision of three Archaean blocks/microcontinents (Barbosa and Sabaté, 2004), one of which – the Serrinha block – contains two main mafic dyke swarms that show field relations relevant for the tectonic reconstruction of orogenic belts. Therefore, the aim of this paper is to present new field relations and geochronology for one of these mafic dyke swarms (the Uauá mafic dyke swarm) and discuss its relevance for tectonic reconstruction of Palaeoproterozoic orogenic belts.

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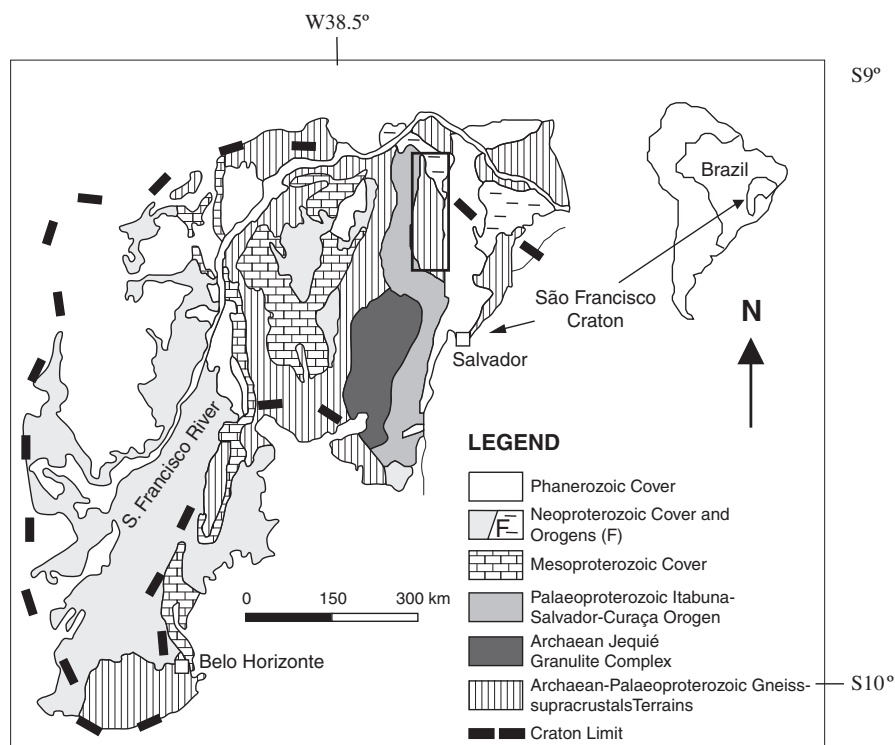
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## Regional Geology

The main geological features of the São Francisco Craton are outlined in Teixeira and Figueiredo (1991) and Teixeira et al. (2000). In general, the São Francisco Craton consists of Archaean to Palaeoproterozoic high-grade (migmatite, granulite) gneisses and granite-greenstone supracrustal terranes overlain by Meso- to Neoproterozoic platform-type cover (Fig. 2.1).

The high-grade terranes, mostly exposed in Bahia state (Fig. 2.1), are separated into the Neoarchaeal Jequié migmatite-granulite complex (Alibert and Barbosa, 1992; Barbosa and Sabaté, 2004), the Mesoarchaeal to Palaeoproterozoic Serrinha block (Mello et al., 2006; Rios et al., 2009; Oliveira et al., 2002, 2010a), and the Neoarchaeal Itabuna-Salvador-Curaçá orogen (Delgado et al., 2003, Oliveira et al., 2004a, 2010a; Barbosa et al., 2008).

Tectonic models proposed for the Itabuna-Salvador-Curaçá orogen involve basement reworking (Silva et al., 1997; Oliveira et al., 2000, 2004a, b), accretion of continental margin and oceanic arcs, and plutonic complexes to Archaean blocks (Teixeira and Figueiredo, 1991; Delgado et al., 2003; Oliveira et al., 2004b, 2010a)



**Fig. 2.1** The São Francisco Craton with the main tectonic units and location of the northern and southern segments of the Itabuna-Salvador-Curaçá orogen. *Box indicates Fig. 2.2*

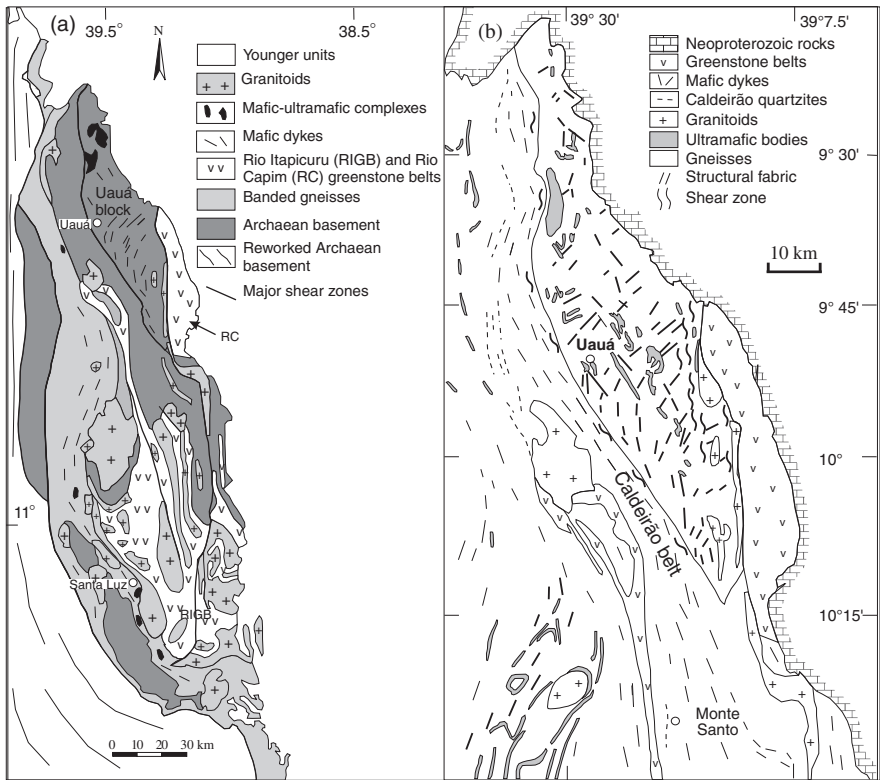
and final continental collision between 2,084 and 2,039 Ma, i.e. the age interval for the peak of high-grade metamorphism (Silva et al., 1997; Mello et al., 2006; Oliveira et al., 2002, 2010a).

Barbosa and Sabaté (2004) proposed that four Archaean tectonic blocks, namely Gavião, Serrinha, Jequié and the Itabuna-Salvador-Curaçá orogen have collided during the Palaeoproterozoic orogeny.

Because the Uauá mafic dykes lie within the Serrinha block, geological information on this block is relevant.

**Serrinha Block**

The Serrinha block, or microcontinent (Fig. 2.2) comprises a basement complex of migmatites, banded gneisses, orthogneisses, mafic dykes and mafic-ultramafic complexes. The banded gneiss unit is the end product of deformation of migmatites



**Fig. 2.2** Geological map of the Serrinha block (modified after Souza et al., 2003) with location of the Uauá block, Calderão belt, mafic dykes, and the Rio Capim (RC) and Rio Itapicuru greenstone belts (RIGB). Their corresponding towns indicate the Uauá and Santa Luz mafic dyke swarms

and mafic dykes; this mafic dyke swarm is called here the Santa Luz mafic dykes. The basement is overlain, or lies in tectonic contact with supracrustal sequences of the Rio Itapicuru and Rio Capim belts, and of the Caldeirão shear belt. Granites intrude all units. The Uauá, Jacurici and Retirolândia gneiss-migmatite complexes (Fig. 2.2) are Mesoarchaeal domains (3,152–2,933 Ma, cf. Oliveira et al., 2010a), or minor blocks in the Serrinha block.

Rio Itapicuru greenstone belt (RIGB in Fig. 2.2a) is a low grade metamorphic supracrustal sequence approximately 180 km long and 30 km wide, divided by Kishida and Riccio (1980) into three lithostratigraphic units: (i) the basal mafic volcanic unit composed of massive and pillowed basaltic flows interlayered with chert, banded iron-formation, and carbonaceous shale; (ii) the intermediate to felsic volcanic unit with metadacites, metandesites and metapyroclastic rocks, and (iii) a metasedimentary pelitic-psammitic unit composed mainly of metapelites and minor chemical sedimentary rocks. The geochronological data indicate a Palaeoproterozoic evolution for this belt, between 2,170 and 2,080 Ma (Mello et al., 2006; Oliveira et al., 2010a).

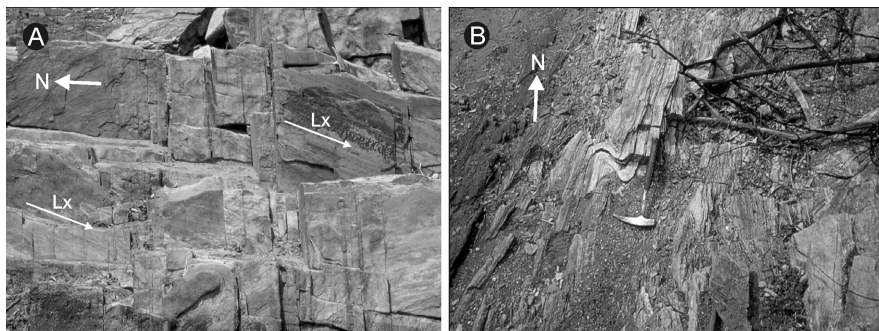
The Rio Capim belt (RC in Fig. 2.2a) and Caldeirão belt lie in contact with the Uauá block and for this reason the three tectonic units will be described in detail in the next section.

### *The Uauá Block*

The Uauá block (Fig. 2.2b) is bordered to the west by the Archaeal-Palaeoproterozoic Caldeirão belt, and to the east it is in fault contact with the Palaeoproterozoic Rio Capim greenstone belt (Oliveira et al., 2010b), or unconformably overlain by Neoproterozoic continental shelf metasedimentary rocks of the Sergipano orogen (Bueno et al., 2009).

The basement of the Uauá block consists mostly of NW-trending banded gneisses of unknown age intruded by layered anorthosite, peridotite and diorite complexes, and tonalite-granodiorite bodies (Mascarenhas and Sá, 1982; Oliveira et al., 1999; Cordani et al., 1999). Most of these rocks have been metamorphosed under granulite facies conditions and later retrogressed to amphibolite grade. Mesoarchaeal ages are widespread in the Uauá block. Paixão and Oliveira (1998) obtained a  $3,161 \pm 65$  Ma whole-rock Pb-Pb isochron for anorthosites of the Lagoa da Vaca layered anorthosite complex and zircon Pb-evaporation age of  $3,072 \pm 20$  Ma for orthogranulites, while Cordani et al. (1999) presented zircon U-Pb SHRIMP ages between 3.12 and 3.13 Ga for the Capim tonalite. Several other Archaeal felsic igneous bodies occur in the Uauá block, some of which, i.e. the Uauá quarry enderbitic granulite and a gneissic granodiorite to the southeast of Uauá town had their zircon grains respectively dated at  $2,933 \pm 3$  and  $2,991 \pm 22$  Ma (Oliveira et al., 2002).

The Caldeirão belt (Fig. 2.2b) comprises a 10 km-wide sheared sequence of steeply dipping quartzites, sillimanite-cordierite-garnet gneiss, granodioritic orthogneisses, mafic rocks and migmatites, all metamorphosed under amphibolite facies conditions. SHRIMP U-Pb age dating indicates a 3,150 Ma for the orthogneisses (Oliveira et al., 2002). To the south, the shear belt dismembers into



**Fig. 2.3** Structural features in shear zone that limits the Uauá block and the Rio Capim greenstone belt. (a) Upright mylonite with low dipping stretching lineations (Lx). (b) Syn-mylonitization asymmetrical fold indicating dextral kinematics

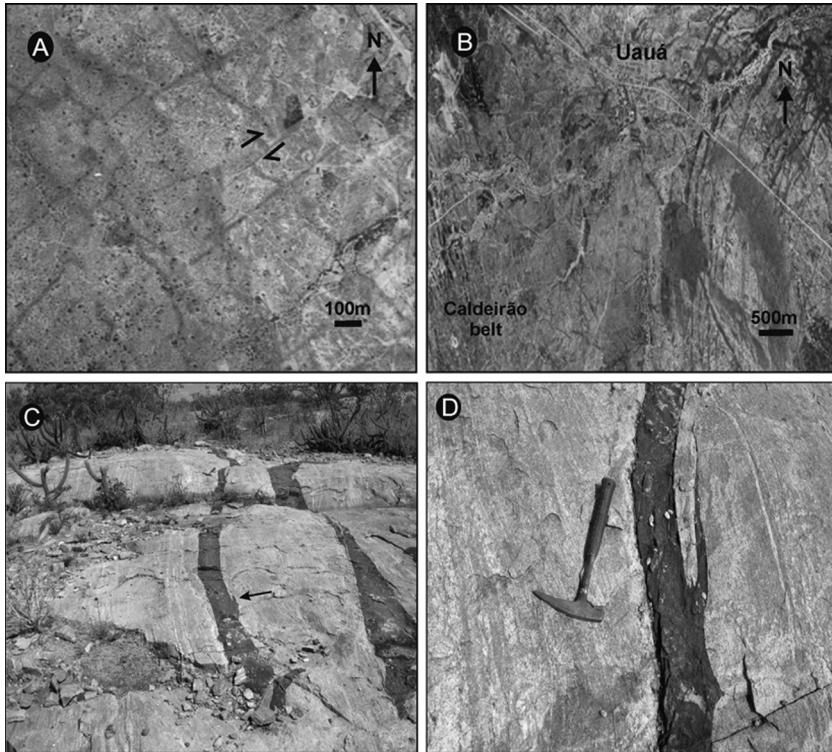
narrow sinistral strike-slip shear zones, one of which (the Main Shear Zone of Chauvet et al., 1997) continues for over 150 km across the Rio Itapicuru greenstone belt. The transition from this belt to the Uauá block is gradational and marked by refolding of older structures in the latter, granite and pegmatite intrusions, and development of shear zones. Syn-deformational titanite in mafic dykes (Oliveira et al., 2000) and detrital zircons in quartzites (Oliveira et al., 2002) constrain a maximum deposition age of 2,700 Ma for the metasedimentary rocks and the regional metamorphic age between 2,039 and 2,077 Ma.

The Rio Capim greenstone belt is a relatively small, 4-km wide, 20-km long, N-, to NW-trending belt of deformed and metamorphosed mafic to felsic volcanic rocks and associated pelitic rocks, intruded by a few plutons ranging in composition from gabbro/diorite to granite (Winge, 1981; Jardim de Sá et al., 1984; Oliveira et al., 2010b). From NW to SE the belt shows mineral assemblages indicative of increasing metamorphic grade from low amphibolite- to granulite facies (Jardim de Sá et al., 1984). Zircon U-Pb ages for the igneous rocks fall in the range 2,148–2,128 Ma (Oliveira et al., 2010b). The Rio Capim greenstone belt lies in contact with the Uauá block, to the west, along the 20–500 m-thick upright Galo do Ouro shear zone with N-S-trending, S-dipping sub-horizontal stretching lineations. S-C relations and syn-mylonitisation asymmetric folds indicate a dextral kinematics for this shear zone (Fig. 2.3). Sheared mafic dykes of the Uauá block close to the shear zone yielded a K-Ar age of ca. 2.0 Ga (Bastos Leal et al., 1994).

## The Uauá Mafic Dykes

### *Dyke Types and Structural Features*

Two mafic dyke swarms intrude the Archaean gneissic basement of the Uauá block, both bimodal, i.e. norite-tholeiite. One dyke swarm trends NW and is made up of metamorphosed tholeiite (now amphibolite) and norite-pyroxenite dykes, whereas



**Fig. 2.4** Field aspects of the Uauá dykes. (a) Aerial photograph showing crosscutting relations between the younger NE-trending dykes and the older NW-trending dykes. (b) Aerial photograph showing the curvature of the younger NE-trending dykes as they approach the Caldeirão belt. (c) Disrupt dykes in the Caldeirão belt. (d) Branching of the main dyke in (c), indicating magma flow towards northeast

the other trends NE and is made up of non-metamorphic tholeiite and norite dykes. On the basis of crosscutting relations and drag folds (Fig. 2.4a) the NE-trending dykes are younger than the NW-trending dykes. In general, the dykes are less than a metre to 30 metres in width and several kilometres long. The norite dykes of the older dyke swarm are mostly coarse-grained cumulates, sometimes with well preserved plagioclase oikocrysts and bronzite-hypersthene chadacrysts, whereas those of the young swarm are fine-grained and show quench textures, such as radiating pyroxene needles. A few quench-textured norite dykes trend also to NW and in this situation distinction between younger and older norite dykes is more difficult. However, the quench-textured norites show Sm-Nd model ages younger than the cumulate norites but similar to the NE-trending tholeiite dykes, and this feature appears to be distinct characteristics of the two norite dykes.



The most interesting structural feature of the NE-trending dykes is the change in their direction. Apart from minor faults and occasional sheared margins, in the central part of the Uauá block the dykes are not significantly deformed and trend to northeast. However, towards the western boundary of the Uauá block, the dykes gradually change direction from NE-SW, through N-S to NW-SE until they become parallel to the Caldeirão shear belt and disappear (Fig. 2.4b). Some of these dykes can be traced within the transition to the Caldeirão belt where they are disrupted or boudined, and metamorphosed to amphibolites (Fig. 2.4c). In spite of deformation, in low-strain zones the dykes still preserve flow indicators, such as dyke branching (Fig. 2.4d), suggesting magma flow towards northeast.

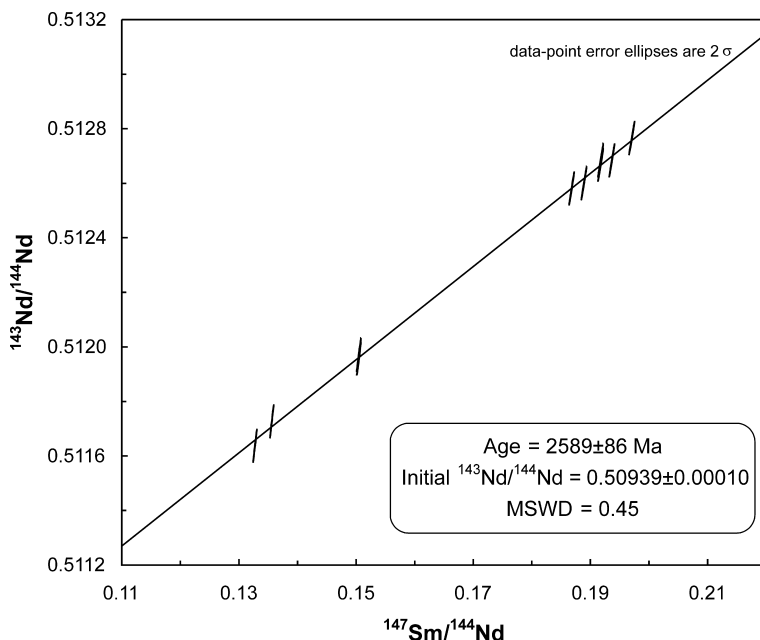
### *Sm-Nd Geochronology*

Earlier attempts to date the Uauá dykes by the U-Pb technique on zircon grains have not succeeded owing to zircon inheritance from the basement. For this reason, whole-rock Sm-Nd isotope data were obtained for both NE-trending tholeiite and norite dykes. The analyses were carried out at the Isotope Geochemistry Laboratory of the University of Kansas, USA, following the general procedures of Patchett and Ruiz (1987). Depleted mantle Nd model ages ( $T_{DM}$ ) were calculated according to DePaolo (1988), and ISOPLOT (Ludwig, 1999) was used to calculate isochrons.

Four norite and six tholeiite dykes were analysed (Table 2.1), all of them with  $T_{DM}$  ages in the range 2.52–2.83 Ga. The older NW-trending dykes have  $T_{DM} > 3.0$  Ga and were not included here. The Sm-Nd reference isochron obtained with the ten dyke samples yielded the age  $2,589 \pm 86$  Ma (Fig. 2.5). Although this result can be revised in the future, as more robust age data are available (e.g. U-Pb in baddeleyite), the 2,589 Ma age is considered as the approximate emplacement timing of the NE-trending dykes.

**Table 2.1** Sm-Nd isotope data for samples of the NE-trending Uauá mafic dykes

Sample	Dyke type	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	( $\pm 1\sigma$ )	$T_{DM}$ (Ga)
MP-07	Quench norite	4.823	21.501	0.13561	0.511727	14	2.59
MP-34	Quench norite	5.313	24.197	0.13274	0.511637	13	2.67
EO-119.1	Quench norite	4.022	16.162	0.15048	0.511957	12	2.62
EO-118.2	Tholeiite	1.887	5.952	0.19174	0.512684	33	2.52
MP-02	Tholeiite	1.821	5.587	0.19707	0.512766	14	–
UA96-3.2	Tholeiite	1.494	4.664	0.19367	0.512684	13	2.83
LR-34-F	Tholeiite	1.410	4.446	0.19174	0.512668	19	2.66
LR-38-F	Tholeiite	1.567	5.070	0.1868	0.512581	13	2.66
UA96-2.1	Tholeiite	1.881	6.020	0.1889	0.5126	14	2.79
EO-47.2	Quench norite	4.382	17.610	0.15046	0.51197	16	2.61
	NW-trending						



**Fig. 2.5** Whole-rock Sm-Nd isochron for the young tholeiite-norite dykes

## Discussion

The Uauá block is a fault-bound Mesoarchaean terrane sandwiched between two contrasting Palaeoproterozoic tectonic domains, namely the Caldeirão shear belt to the west and the Rio Capim greenstone belt to the east.

Two bimodal norite-tholeiite mafic dyke swarms occur in the Uauá block, the youngest of which trends northeast and is ca. 2,580 Ma old. This dyke swarm shows a curvature in dyke direction from NE, through NS to NW as the Caldeirão belt is approached. This feature is interpreted as large-scale drag folds, indicating a left-lateral displacement of the Uauá block in relation to the Caldeirão belt. On the eastern boundary of the Uauá block, kinematic indicators in shear zones show right-lateral displacement of the Uauá block relative to the Rio Capim belt. Overall, combination of the sinistral kinematics in the Caldeirão belt with the dextral kinematics in shear zones between the Uauá block and the Rio Capim belt indicates bulk movement of the Uauá block from present-day south to north.

Northwards extrusion of the Uauá block has occurred during the final oblique continent collision that formed the Itabuna-Salvador-Curaçá orogen. Time constraints for this collision is provided by SHRIMP U-Pb ages on metamorphic rims on zircon grains from quartzite of the Caldeirão belt and orthogneisses of the Itabuna-Salvador-Curaçá orogen (Silva et al., 1997; Oliveira et al., 2002, 2010a), showing high-grade metamorphic ages between 2,082 and 2,074 Ma. However, extrusion

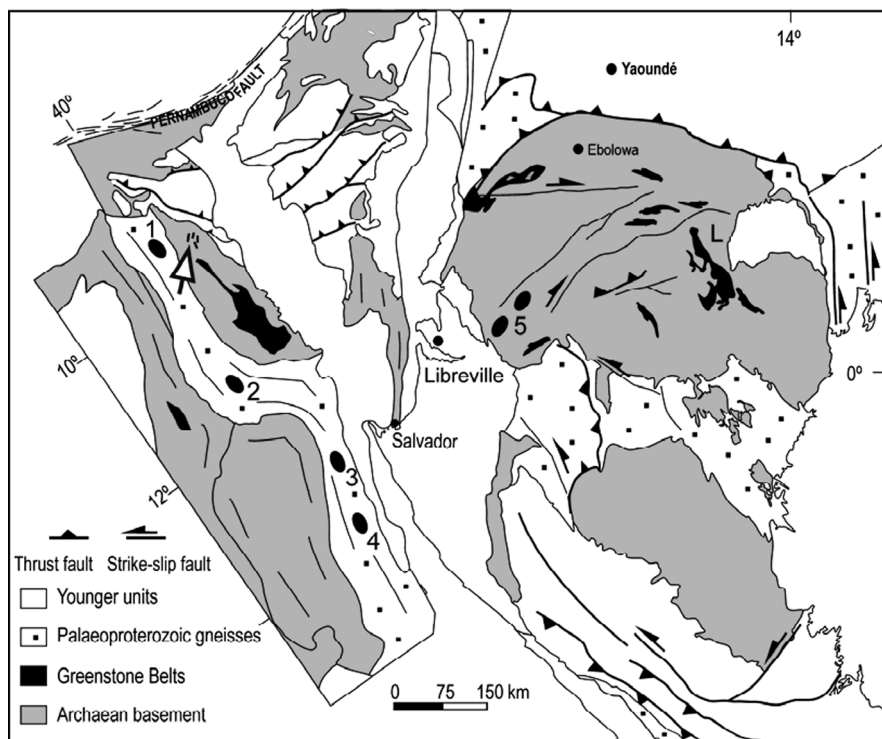


may have lasted longer on the basis of U-Pb age dating on metamorphic syn-deformation titanite grains in boudined mafic dyke of the Caldeirão belt, with the age  $2,039 \pm 2$  Ma (Oliveira et al., 2000).

Terrane extrusion is a common feature in Phanerozoic collisional orogenic belts such as the Alpine-Himalayan belt (e.g. Tapponnier et al., 1982; Lacassin et al., 1997; Hollingsworth et al., 2008) and in Neoproterozoic belts (e.g. Goscombe et al., 2005; Van Schmus et al., 2008; Bueno et al., 2009), but its recognition in Archaean and Palaeoproterozoic orogens is poorly constrained. Indeed, in the Palaeoproterozoic Nagssugtoqidian orogen (West Greenland) Manatschal et al. (1998) describe deformation phases indicative of extrusion associated with exhumation of the belt, while in the Trans-Hudson orogen, which is considered as the Palaeoproterozoic analogue of modern accretionary orogens, Corrigan et al. (2009) just speculate that the Sask Craton extruded southward during impingement of the Superior Craton ca. 1.83 Ga. In contrast, the gradual change in direction (drag folds) of the NE-trending, Neoproterozoic Uauá mafic dyke swarm during oblique continent collision is a first-order example of lateral extrusion in Palaeoproterozoic orogens.

How far has the Uauá block displaced from its original location is unknown but the suggested northeastwards magma flow direction deduced from dyke branching may be useful for regional correlations and metallogenesis. If the NE-trending Uauá dykes were the failed arm of an Archaean rift then the complement magma plumbing system, with basalts and the deep-seated mafic-ultramafic equivalents, should be located somewhere to the west-southwest (present-day coordinates) of the Uauá block. Figure 2.6 shows the younger Uauá mafic dyke swarm and potential correlative mafic-ultramafic bodies and greenstone belts in a pre-drift configuration of the São Francisco-Congo Craton.

The nearest mafic rocks that could fit the triple arm of a rift is the Santa Luz mafic dyke swarm which build up the mafic portion of the Serrinha block regional banded gneiss and trends mostly to north and northwest (Fig. 2.2). However, the recent zircon U-Pb SHRIMP age of  $2,705 \pm 5$  Ma for this swarm (EP Oliveira, unpublished data) makes correlation with the NE-trending Uauá dykes unsustainable. Also, no  $\sim 2.58$  Ga greenstone belt is known in this part of the São Francisco Craton or in the Congo Craton. In the former the Rio Capim and Rio Itapicuru greenstone belts are Palaeoproterozoic (2.17–2.08 Ga, cf. Oliveira et al., 2010a) whereas the Mundo Novo greenstone belt, to the west of the Itabuna-Salvador-Curaçá orogen is ca. 3.3 Ga old (Peucat et al., 2002). Mafic-ultramafic bodies are common in the Itabuna-Salvador-Curaçá (shown as black ellipses in Fig. 2.6) and may correlate in age with the Uauá dykes. Indeed, the Caraíba and São José do Jacuípe noritic-gabbroic complexes are the only rocks dated so far and they are similar in age to the Uauá dykes (ca. 2,580 Ma, cf. Oliveira et al., 2010a). Farther south, several mafic-ultramafic complexes have been recognized, of which the Ni sulphide-bearing Mirabela gabbro and the Rio Piau layered anorthosite are potential correlatives to the Uauá dykes; however, their ages have not been constrained yet. In the Congo Craton the youngest greenstone belt (L in Fig. 2.6) was dated at 2,970–2,940 Ma (whole-rock Pb-Pb isochron and zircon Pb-Pb evaporation), whereas the Kinguele line of mafic-ultramafic complexes yield a 2,783 Ma Pb-Pb isochron (Feybesse et al.,



**Fig. 2.6** Pre-drift geological correlation between Archaean-Palaeoproterozoic terranes of the São Francisco-Congo Craton showing the NE-trending Uauá mafic dykes in relation to the main greenstone belts and mafic-ultramafic bodies (*black ellipsis*). *Unfilled arrow* indicates the Uauá dykes and their probable magma-flow direction. Geology simplified from Barbosa (1994) and Feybesse et al. (1998). Mafic-ultramafic complexes: 1-Caraíba, 2-São José do Jacuípe, 3-Mirabela, 4-Rio Piau, 5-Kingueue

1998). Therefore, on the basis of these ages it appears that the São Francisco Craton is the most potential area to look for tectonic correlation with the Uauá dykes, an exercise that must be pursued in the future.

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