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METAMORPHIC AND STRUCTURAL EVOLUTION OF THE GORE-GAMBELLA AREA, WESTERN ETHIOPIA

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ABSTRACT: The Gore-Gambella area comprises of three lithotectonic units: the Birbir domain, an assemblage of mafic to felsic intrusive and extrusive rocks and mainly volcanogenic sedimentary rocks, is metamorphosed to low amphibolite facies. It is enclosed between the Baro and Geba domains, that consist of upper amphibolite facies ortho- and paragneisses and migmatites. The Birbir domain is a major transcurrent shear belt, in which all rock units have been mylonitized to varying degrees. Foliations are steep and primarily sub-parallel to layering; extension lineations are sub-horizontal. The boundaries of the domain are tectonic, and deformation is concentrated near the western contact, in the 5 km-wide Birbir shear zone. Gneissic layering in the high grade domains is openly folded, demonstrating at least two periods of deformation; lineations are shallow like those of the Birbir domain. There are steep gradients in metamorphic conditions at the domain boundaries: diagnostic metamorphic assemblages in the western Birbir domain indicate ca. 520° C and 4 kbar, whereas those in the eastern Baro domain denote ca. 700° C and 7 kbar.

Key words/phrases: accreted-arc, amphibolite facies, coeval, mylonite, Pan-African rocks

INTRODUCTION

The Precambrian rocks of Ethiopia lie between the predominantly gneissic rocks of the Mozambique Belt, to the south, and the Arabian-Nubian Shield (ANS) to the north. The ANS consists of at least five northerly-trending volcanic-sedimentary belts, largely separated by strips that contain ophiolitic rocks (Vail, 1985). These are now generally accepted as accreted arc complexes of Pan-African age with intervening remnants of oceanic crust; they evolved during the interval 1000–500 Ma ago (Teklewold Ayalew *et al.*, 1990; Teklewold Ayalew and Samuel Gichile, 1990; Shackleton, 1993; 1994; Stern, 1994). Within Ethiopia the Precambrian-Early Palaeozoic rocks contain elements that resemble both of the above terranes. The Precambrian rocks of Ethiopia outcrop in four areas around the plateau margins; the western Ethiopian Shield (WES) is the largest of these exposures (inset - Fig. 1). The WES is a mosaic of high grade gneissic domains separated by north-trending belts of lower metamorphic grade that contain recognizable volcanic and sedimentary units, many of which are highly sheared, intruded by a diverse suite of plutons. The contact and age relationships between adjacent rocks of contrasting metamorphic grade have been a source of controversy, and nowhere has the relationship between the two groups of rocks been conclusively resolved.

The Gore-Gambella transect, comprising of 3025 km^2, is bounded by latitudes 8°00′ and 8°30′N and longitudes 34°45′ and 35°15′E (Fig. 1). The area includes representatives of the gneissic and volcano-sedimentary domains, in the area with excellent exposures and relative accessibility. In this paper the metamorphic and structural data of the area is provided. The results of the geochemical and isotopic studies have been reported elsewhere (Teklewold Ayalew *et al.*, 1987; Teklewold Ayalew *et al.*, 1990; Teklewold Ayalew and Peccerillo, 1997).

LITHOLOGY

Mengesha Tefera and Seife Michael Berhe (1987) recognized three major domains in the Gore-Gambella area: the Baro and Geba domains (Fig. 1) consist of gneisses and migmatites of upper amphibolite grade, whereas the Birbir domain (Fig. 1) that lies between them is made up of lower grade rocks containing abundant mafic schists. The domain boundaries exhibit low-angle structural discordance on the regional scale and there is apparent transposition of east-west trends in the Geba domain toward concordance with the Birbir domain boundary. The map area contains representatives of all three domains (Fig. 1). Map units fall in three main groups: (1) metamorphosed volcanic, sedimentary and hypabbysal rocks; (2) gneisses; and (3) intrusive and meta-intrusive rocks.

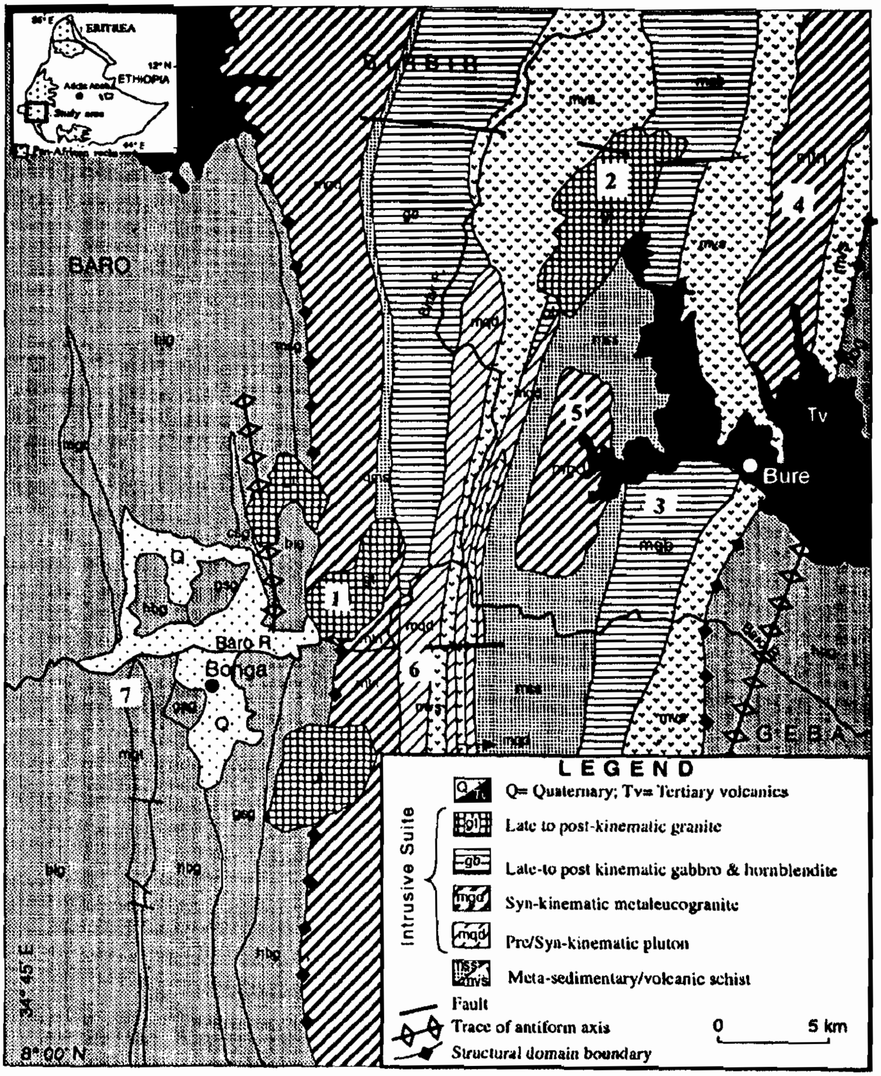

Fig. 1. **Generalized geology of the Gore-Gambella area.** mss, metasedimentary schists; mvs, metavolcanic-sedimentary rocks and mylonite; csg, calc-silicate gneiss; gsg, garnet-sillimanite and garnet-cordierite-gedrite gneisses; qms, quartz-muscovite schist; msg, muscovite-bearing schist and gneiss; hbg, hornblende-biotite gneiss and amphibolite; big, biotite ± hornblende gneiss; intrusive and meta-intrusive units: (1), Bonga; (2), Mao; (3), Bure; (4), Haya; (5), Goma; (6), Birbir; and (7), Baro; mgb, metagabbro; mqd, meta-quartz diorite; mtn, metatonalite; mgd, metagranodiorite; mgt, metagranite; gb, gabbro; gt, granite; Tv, Tertiary volcanic rocks; Q, alluvium. (Compiled by Teklewold Ayalew and Moore, 1989.)

Metamorphosed sedimentary, volcanic and intrusive rocks

Metasedimentary schists (**mss**) underlie much of the area east of the Birbir River, and consist of well-preserved metawacke and pelite. The metasedimentary rocks are interlayered with sheets of mylonitic quartz diorite and biotite-hornblende schist. Strong deformation obscures the contact relationships with the mylonitized plutonic rocks. Lenses of polymictic, coarse volcaniclastic rocks occur in contact with the Goma pluton (Fig. 1) along its NNE margin. The clasts are poorly-sorted and sub-rounded, matrix-supported and mainly of rhyolite and andesite. Marble locally occurs as thin interlayers up to 6 m wide. Amygdaloidal flows of andesitic composition, at least 3–4 m thick, are intercalated with wacke. Primary sedimentary features such as cross-lamination, load casts, convolute and graded bedding, common in metawackes, indicate that turbidity flows have been responsible for at least some of the sedimentation. Associated coarse volcaniclastic rocks suggest rapid deposition by sediment gravity flows close to an area being uplifted and rapidly eroded. Rounding of the clasts indicates subaerial transport and/or shoreline abrasion and implies a subaerial volcanic source area. Metavolcanic rocks and mylonites (**mvs**) occur between sheets of metaquartz diorite (**mqd**) and metasedimentary rocks (**mss**), on the scale of hundreds of metres thickness. North and south of Bure (Fig. 1) metavolcanic rocks, mainly mafic in composition, are interleaved with sheets of metagabbro (Bure pluton, Fig. 1). Primary igneous textures include plagioclase laths and hornblende phenocrysts in rocks of andesitic composition. Most mylonitic rocks have a lenticular foliation and mineral aggregate lineation. Near the Baro-Birbir river confluence, mafic and felsic dykes cut the unit and are disrupted by shearing. Quartz - muscovite schist and conglomerate (**qms**) that form a NNE-trending wedge along the western border of the Birbir Domain, consist of quartz-muscovite and quartz-chlorite schist with rare garnet in addition to subordinate layers of quartzite. A lense of quartz-pebble conglomerate, containing pebbles up to 2 cm in diameter, within the quartz-muscovite schist indicate a clastic origin for rocks of the unit.

Gneisses (undifferentiated)

Most of the area west of Bonga (Fig. 1) is underlain by layered and relatively uniform gneisses. The predominant rock types are strongly foliated, biotite and hornblende-biotite quartzofeldspathic gneisses (**big**; **hbg**). Minor quartzite and amphibolite layers occur within **hbg**. Some of the gneisses are migmatitic, cut by sub-concordant lenses of granitic and pegmatitic material. Discordant dykes and pods of pegmatite also occur. Uniformity and modal composition suggest that the majority of **big** and **hbg** are tonalitic or granodioritic orthogneisses.

Paragneisses dominate the succession along the eastern side of the Baro domain, north and south of the Baro River. Garnet - sillimanite gneiss (**gsg**) underlies the area immediately east of Bonga (Fig. 1). It is a composite unit consisting of interlayered aluminous and calc-silicate gneisses with subordinate amphibolite. Cordierite-gedrite - bearing rocks are interlayered with the aluminous gneisses. Along the eastern boundary of the sillimanite gneiss is a well-exposed section of layered calc-silicate gneiss (**csg**). A narrow belt of muscovite-bearing gneiss (**msg**) that occurs along the eastern border of the biotite gneisses (**big**) probably represents a retrograde metamorphic equivalent of that unit.

METAMORPHISM

All the rocks in the Gore-Gambella area, except the latest intrusive bodies and the overlying Tertiary volcanics, are metamorphosed. The broad division of the area into domains is based as much on metamorphic grade as on primary lithology. The Baro and Geba domains are characterized by medium to coarse grained quartzofeldspathic gneisses and migmatites that show no evidence of primary sedimentary or volcanic features. For the most part they lack muscovite; sillimanite is present with potassic feldspar in aluminous rocks and clinopyroxene accompanies dark coloured hornblende in mafic rocks. These indicators are typical of upper amphibolite facies metamorphism. The metamorphic orthopyroxene and dark quartz and potassic feldspars that are characteristic of granulite facies have not however been observed anywhere in the area. In contrast, rocks of the Birbir domain are typically fine grained schists, that locally exhibit fine-scale sedimentary and volcanic structures. Muscovite is abundant in rocks of suitable composition (i.e., rich in alumina), chlorite was locally stable and plagioclase is sodic even in mafic rocks. Pelitic rocks west of Bure contain the assemblage garnet-andalusite-staurolite, with chlorite, biotite, quartz and sodic plagioclase. In some of the plutonic bodies, primary textures are preserved that involve relict high temperature minerals such as pyroxene and calcic plagioclase. Where recrystallization is extensive, the plutons commonly exhibit mylonitic textures and comprise assemblages similar to those of the enclosing schists. These features are all indicative of a lower regional metamorphic grade than the adjacent domains, in the low amphibolite facies. Beyond these general indications and the local evidence provided by suitable assemblages, it is not possible at present to precisely plot isograds in most of the map area.

Mineral parageneses and P-T conditions

Birbir domain: Metamorphic mineral assemblages from metasedimentary schist (mss) and hornblende and biotite schist (hbs) units include:

1) quartz-muscovite-biotite-oligoclase-epidote-calcite;
2) quartz-muscovite-biotite-staurolite-andalusite-chlorite- (garnet); and
3) quartz-oligoclase-microcline-hornblende-biotite-epidote-(actinolite)

that indicate lower amphibolite (epidote-amphibolite) facies regional metamorphism, in the staurolite zone. Chlorite is abundant only in muscovite-free rocks and as a highly magnesian variety in meta-ultramafic (?) schists; in other rocks it can mainly be ascribed to retrograde alteration. Oligoclase (An_{20-30}), rather than albite ($An_{<10}$), is the typical plagioclase. Rocks with assemblage (2), between the Goma and Mao plutons, contain large porphyroblasts of andalusite and staurolite coexisting with biotite, muscovite and Fe-rich chlorite. Garnets are millimetre-scale and thus probably Mn-rich (Hounslow and Moore, 1967). The assemblage is indicative of low pressure-medium temperature metamorphism, corresponding to bathozone 1 of Carmichael (1978). Staurolite occurs as well-formed euhedral, sieve textured porphyroblasts, partly replaced by a fine-grained mixture of quartz, feldspar, biotite and muscovite. Chlorite occurs as rims around staurolite but also independently in the matrix. Both staurolite and andalusite overgrew the foliation, as they contain inclusion trails of quartz and biotite flakes that are continuous with those in the matrix. A concentric overgrowth around andalusite consists of muscovite rimmed by chlorite with a fine grained staurolite crystals. These textures imply a reaction isograd that may be expressed by the equation:

staurolite + chlorite + muscovite = andalusite + biotite + quartz + water

The appropriate part of a petrogenetic grid constructed by Carmichael (1985) is shown in Fig. 2a. The reaction is univariant at constant H_2O activity; it takes place within the andalusite stability field at a temperature of about 520–530° C and 3.5–4.1 kbar pressure.

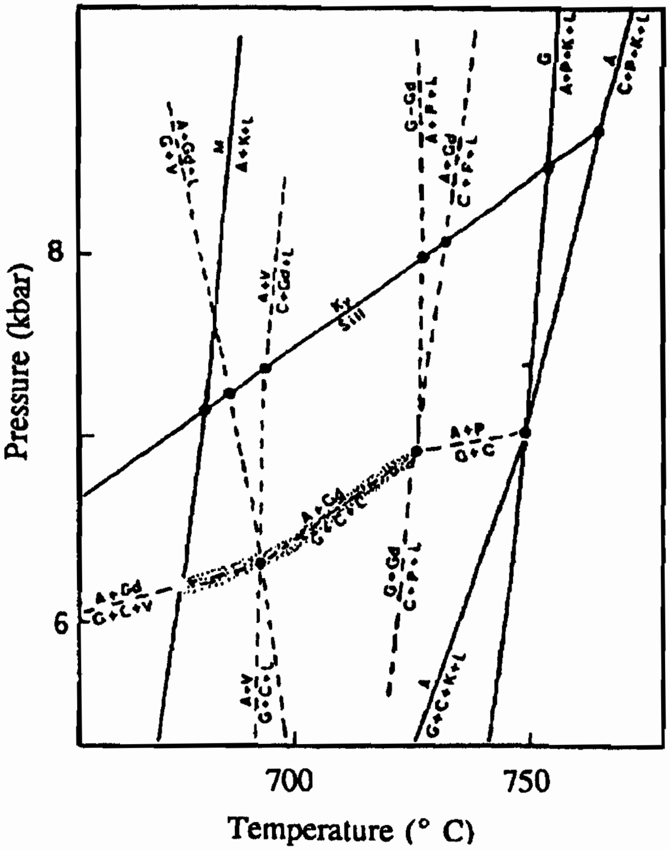

Fig. 2(a). Petrogenetic grid after Carmichael (1985) showing reactions among assemblages that contain biotite, plagioclase and quartz. Stippled curve denotes assemblage observed in metapelite of the Birbir domain. Mineral abbreviations: A, Al_2SiO_5; (And, andalusite; Ky, kyanite; sill, sillimanite); C, cordierite; Ch, chlorite; G, almandine garnet; M, muscovite; S, staurolite; V, fluid. Solid dots represent invariant points. Unit activity of water is assumed.

In view of the locality, between two large intrusive bodies, it might be suggested that the above conditions reflect contact, rather than regional metamorphism and are not typical of the Birbir domain as a whole. The plutons are however both affected, in varying degree, by movements along the Birbir shear zone, that are associated with major isotopic re-equilibration (Teklewold Ayalew *et al.*, 1990). As no major mineralogical changes appear to have taken place in the pelitic rocks during these events, it is suggested that the assemblages reflect regional conditions at the time.

Mineral assemblages in the meta-igneous rocks of the Birbir domain can be represented by the association:

4) quartz-microcline-oligoclase-biotite-hornblende-epidote-titanate,

without chlorite, that also indicates low amphibolite facies metamorphism. Metamorphic conditions associated with the mylonitic rocks and those virtually unaffected by the shearing both reflect the same grade, suggesting that metamorphic conditions have not changed throughout the duration of shearing. Hornblende and biotite have overgrown fine, probably mylonitic schistosity. Nevertheless, the presence of actinolite after hornblende, and chlorite veinlets, in the mylonitic rocks indicate limited retrograde effects during or after the shearing event.

Baro domain: Several diagnostic metamorphic mineral assemblages have been identified in the aluminous and calc-silicate rocks of units (garnet-sillimanite gneiss (gsg) and calc-silicate gneiss (csg)) along the eastern margin of the Baro domain. These include:

5) sillimanite-garnet (almandine)-cordierite-orthoamphibole-plagioclase-biotite-quartz;
6) sillimanite-garnet (almandine)-K feldspar-biotite-quartz; and
7) hornblende-clinopyroxene (diopside)-epidote-titanate.

Assemblages (5) and (6) define a very restricted P-T range for the peak metamorphic conditions that affected garnet-sillimanite gneiss unit (gsg). Assemblage (5), in which cordierite occurs as rims on gedrite (Plate 1A), indicates a reaction isograd:

sillimanite + gedrite (orthoamphibole) = almandine + cordierite + water

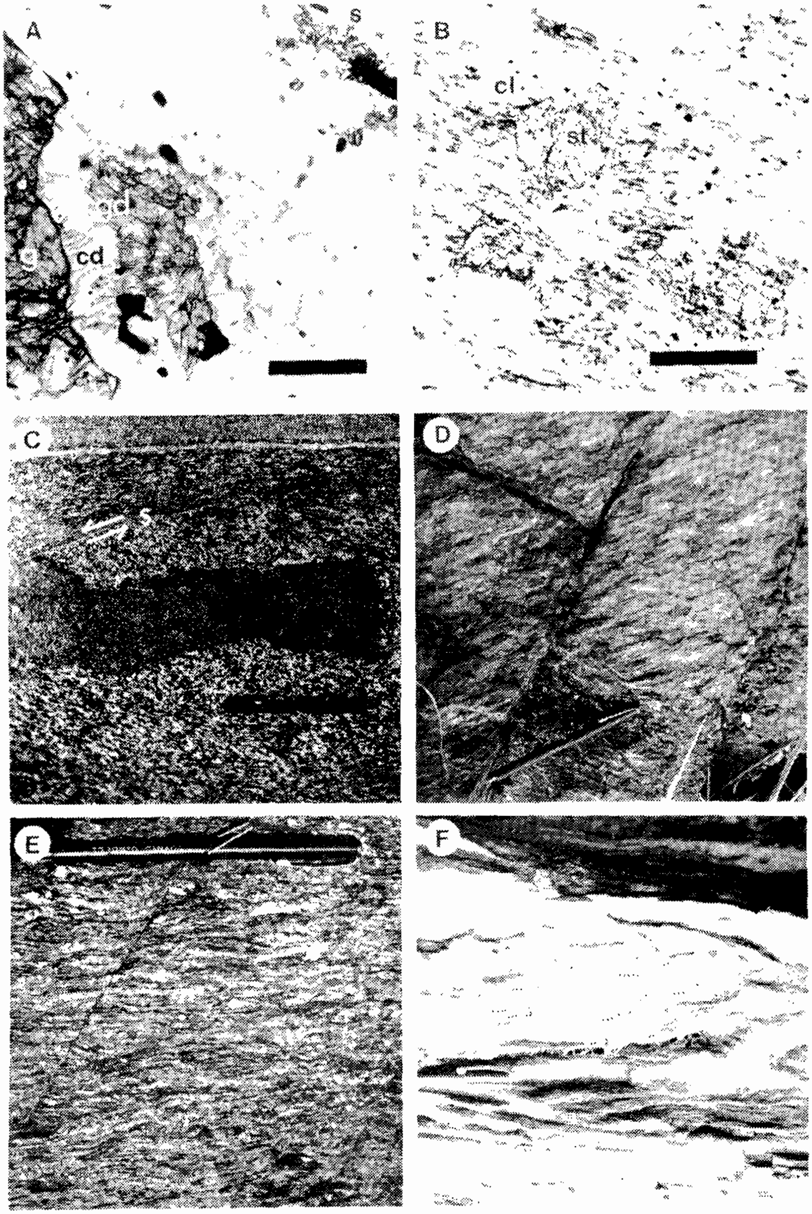

Plate 1: **Metamorphic mineral assemblages in pelitic rocks (A,B) and strain features in the Birbir shear zone (C-F).** See next page for the notations A, B, C, D, E and F.

A, Assemblage almandine-cordierite-sillimanite from unit (gsg) of the Baro Domain. cd, cordierite; s, sillimanite; gd, gedrite; g, garnet. PPL. scale bar is 0.5 mm long. Sample # UP49a, locality: Bonga.

B, Staurolite porphyroblasts in fine-grained matrix of quartz, biotite, muscovite and chlorite in unit (mss). st, staurolite; cl, Fe-rich chlorite; b, biotite. PPL. Scale bar is 1 mm long. Sample # OY032, locality: 11 km west of Bure.

C, Flattened mafic xenolith in weakly to moderately foliated Birbir quartz diorite (mqd). Ductile shear zone at top (s) truncates xenolith and has sinistral sense. Main road 10 km east of Bonga. Pen magnet is 12 cm long.

D, Mylonitic extension lineation in (mqd) defined by aggregates of biotite and quartz, parallel to pen. Birbir River, 5 km north of confluence with Baro River.

E, Well-defined mylonitic foliation in metagranodiorite (mgd) defined by biotite and hornblende streaks, and flattened quartz and feldspar. sb: shear bands, indicating sinistral shear sense. Two kilometres north of main road, 11.5 km west of Bure.

F, Folded mylonitic foliation in Birbir quartz diorite (mqd). One kilometre north of main road, 12 km west of Bure.

Part of a reaction grid developed by Carmichael (1985) for Fe-Mg rich pelites in a six component system: SiO_2-Al_2O_3-FeO-MgO-Na_2O-K_2O (without sufficient K to form muscovite), has been used to interpret this reaction isograd. The reaction is univariant at constant H_2O activity and occurs at pressures of 5.8–7.0 kbar and temperatures between 630–730° C (Fig. 2b). The absence of muscovite from assemblage (6) shows the peak metamorphic temperatures were above the reaction isograd:

muscovite + quartz = sillimanite + microcline + water

The reaction, in combination with (5), restricts conditions of formation of the aluminous rocks to within 680–730° C and 6.3–7.0 kbar (Fig. 2b). The presence of muscovite-bearing assemblages in muscovite-quartz schist unit (**mqs**), from the western side of the Birbir domain, indicates an increase in metamorphic grade toward the west where muscovite-free, sillimanite-bearing assemblages prevail. The sillimanite-free, muscovite-bearing assemblages of unit **mqs** have primary clastic textures indicating that they are not retrograde assemblages from unit **gsg**. In rocks of unit **gsg** containing assemblage (5), some garnet porphyroblasts contain quartz inclusion trails with an orientation that is continuous with foliation in the matrix, suggesting a late- or syntectonic period of garnet growth with respect to foliation associated with the main deformation. Orientation of some of the gedrite (orthoamphibole) and sillimanite in the direction of the main foliation suggests that these minerals grew during the development of the gneissic fabric; the growth of garnet porphyroblasts outlasted the deformation.

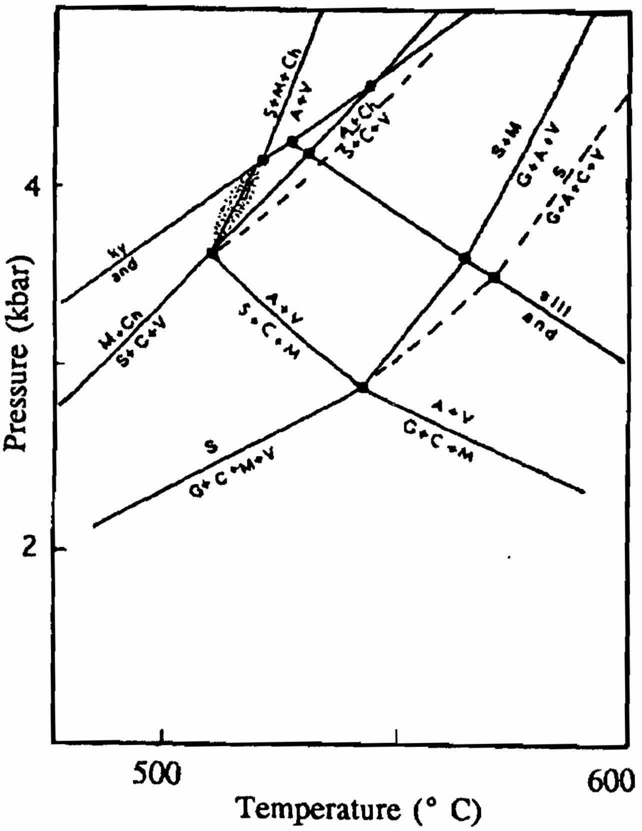

Fig. 2(b). Petrogenetic grid after Carmichael (1985) showing reactions among assemblages that contain biotite, plagioclase and quartz. Stippled curve denotes assemblage observed in metasedimentary schists and gneisses of the Baro domain. Mineral abbreviations and conventions as in Fig. 2(a) plus: Gd, gedrite; K, K-feldspar; L, granitic liquid; P, orthopyroxene. Dashed curves represent reactions in K-deficient rocks.

The origin of the bulk composition associated with assemblage (5) is interesting because of the high content of Mg and Fe, and low K and Ca content, in these rocks. There are at least three alternative modes of origin. The first is that the rocks reflect a premetamorphic bulk composition. Rocks with such characteristics are well known from hydrothermal alteration zones in submarine mafic volcanic rocks, where they form pipes or sheets that may lie below massive sulphides (Burnham, 1979). The association of normal amphibolites, pyritic biotite gneisses and magnetite-bearing quartzites with the gedrite-bearing rocks supports the suggestion of a volcanic-exhalative environment. Similar compositions may also form as a result of the chemical weathering of mafic rocks (Harnois and Moore, 1988). The second explanation involves metasomatic addition of Mg and Fe with simultaneous removal of Ca and alkalies, whereas the third involves enrichment of Mg and Fe by metamorphic differentiation or anatexis. Although there are no obvious sources or sinks of elements to support a metasomatic process, the association of migmatitic rocks could suggest that the Mg-Fe rocks are restites, depleted in alkalies and silica by the extraction of partial melt. The hypothesis however fails to account for the Ca depletion, thus a premetamorphic alteration process is the most probable origin for the cordierite-gedrite-bearing rocks.

Metamorphic gradients: In the Baro domain, the most easterly occurrence of sillimanite (accompanied by quartz and K-feldspar), is only 4 km across strike, measured perpendicular to strike, west of chlorite- (and staurolite ?) bearing schists to the north near the western border of the Birbir domain. The presence of metagranitoid rocks immediately east of the sillimanite-K feldspar assemblage precludes a more precise definition of the metamorphic gradient, but it appears to be steep. Similarly, there is a passage from the fine grained mylonitic schists at the eastern edge of the Birbir domain, across metagranite **(mgt)**, to migmatitic metadiorite in only about one kilometre. The presence along this boundary of muscovite schists with coarse garnet porphyroblasts, and at least one occurrence of kyanite, implies a narrow zone of transition in metamorphic grade.

STRUCTURE

Data on the orientation of planar and linear structures in the Gore-Gambella area are presented in stereographic plots (Fig. 3). There is a predominantly north-south structural grain in the area; foliation trends diverge in the north-central part, corresponding to a widening of the Birbir domain toward the north (see Kazmin *et al.*, 1979, Fig. 2). There is a general subparallelism of layering and metamorphic foliation. Linear features, mainly stretching lineations defined by deformed clasts, minerals and mineral aggregates, plunge shallowly to north and south through out the region.

Birbir domain: Rocks of the Birbir domain have predominantly north-south striking foliations that dip steeply and predominantly toward the west (Fig. 3). These steep attitudes are confined to the belt bounded by the mylonitic leucogranite (**mgt**) at Bure on the east, and the westernmost layer of muscovite-quartz schist (**mqs**) on the west. Sedimentary structures such as cross-lamination and graded bedding are well preserved in the metagraywacke of **mss**. Although bedding and cleavage are mostly subparallel, bedding-cleavage relations at several localities in the area just west of Bure give stratigraphic facing directions that are easterly, consistent with those indicated by the sedimentary structures. Stretching lineations (Fig. 3) mainly plunge less than 20° to north and south. Map-scale folds are not seen and mesoscopic folds are not abundant, but those observed mainly shallowly-plunging hinges that lie in similar orientations to the stretching lineation. At least some of the few steeply-plunging folds observed are of mylonitic foliation (see below).

The origin of the main foliation in the Birbir domain is a matter of conjecture. It may be related to the formation of early folds that are unrecognizable because the stratigraphy is complex and because they have been dismembered by synchronous and/or later shear. Alternatively, foliation may result from syntectonic recrystallization during early shearing.

Birbir shear zone (BSZ)

Mylonitic rocks occur throughout the Birbir domain, but are especially prominent in the western half, where they are mainly concentrated in a 5 km wide zone that extends from the western contact of the Goma pluton on the east (Fig. 1) across the Birbir to the west. This feature, the **Birbir shear zone,** is a NNE-striking region of high ductile strain consisting of numerous mylonite zones separated by less-strained rocks. Dips of the mylonitic foliation are typically steep to vertical (**Plate 2A**). The rocks affected by shearing have extension lineations that gently plunge north or south, suggesting transcurrent movement (**Plate 1D**). Rocks of the meta-quartz diorite (**mqd**) and hornblende and biotite schist (**hbs**) are most intensely mylonitized; **mqd** commonly is converted to augen schist exhibiting S/C and shear band fabrics (**Plate 1E**). The mylonitic foliation is asymmetrically folded in places (**Plate 1F**). Folds vary from open to tight; the tightest have hingelines that are closest to the stretching direction. This relation suggests progressive rotation of the hinges during a continuous shearing event.

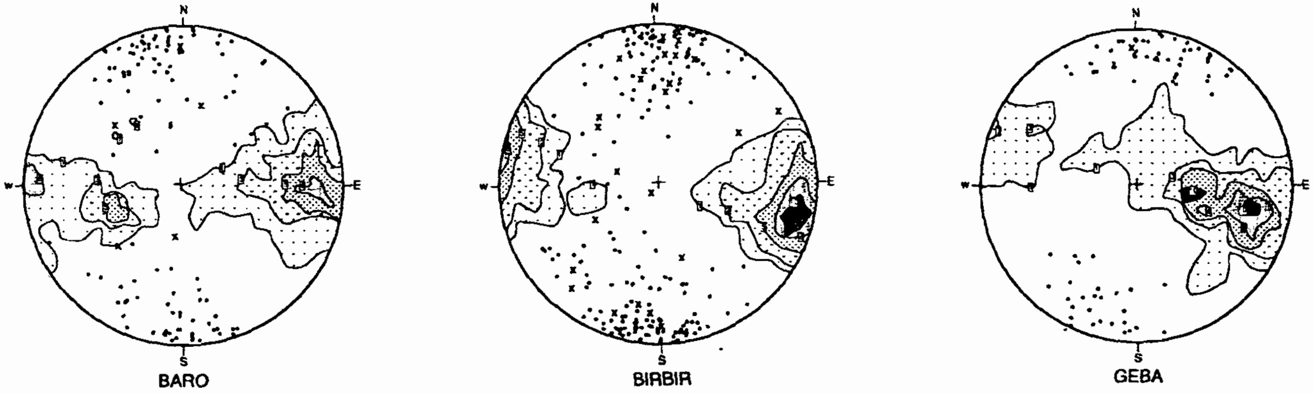

Fig. 3. Equal-area stereographic plots of structural data by domain. Contours represent concentration of foliation poles, as percent of total population per 1% area. Dots, stretching lineations; x, minor fold axes. Total foliation populations: Baro=296; Birbir=519; Geba=118. Total lineations: Baro=138; Birbir=113; Geba=80.

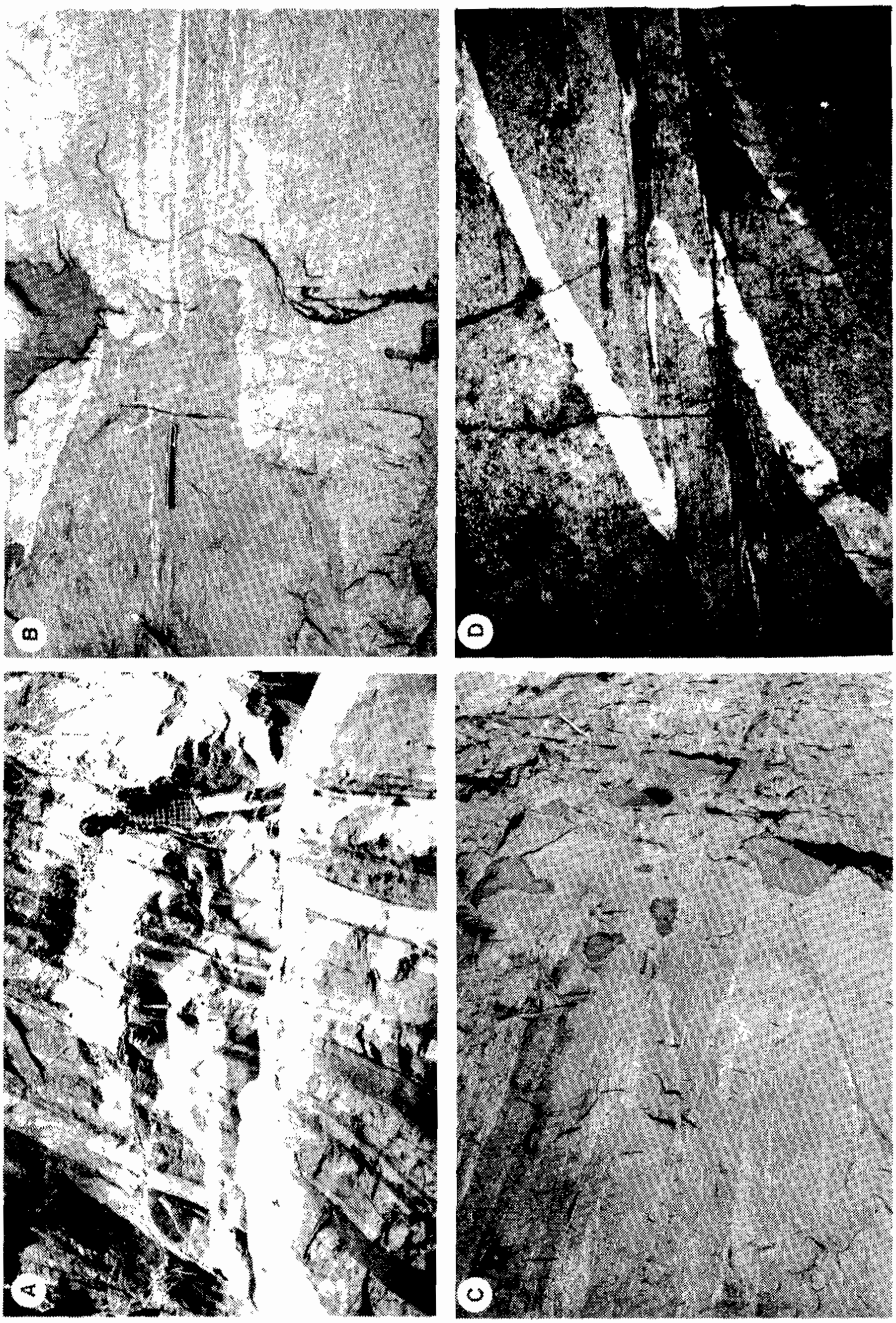

Plate 2. **Deformation in the Birbir shear zone.** **See next page for the notations** A, B, C and D.

A, View toward north of mafic and felsic ultramylonites immediately east of the Birbir River, 5 km north of its junction with the Baro.

B, Fold hinge in a metabasaltic dyke that cuts disrupted remnants of earlier mafic dykes, transposed parallel to N-striking foliation in host metatonalite. Note felsic vein in dyke segment, truncated at centre by the later dyke. Minor folds that close into metatonalite have sharper hinges than those that close into amphibolite, demonstrating lower ductility of the tonalite. South bank of Baro River. Pen magnet 12 cm long.

C, Metabasalt dyke cuts metatonalite at low angle to foliation. Tonalite bears closely spaced lozenges of disrupted, earlier metamafic dykes, At centre of view, by pen magnet, dyke is truncated and shortened along a fault, indicating dextral shear. Same locality and scale as B.

D, Late metagranitic dyke cuts same metatonalite as at B and C, but is sinistrally displaced. One kilometre south of above locality.

Other structures that indicate shear in the BSZ are abundant folded and disrupted mafic and felsic dykes. Mafic dykes are especially well-exposed on the Baro River near the sharp bend 5 km downstream from its junction with the Birbir River, where they display widely varying degrees of deformation (**Plates 2B, C**). Less-deformed dykes cut earlier, more strongly foliated and dismembered dykes, indicating that they were emplaced synchronously with shearing. Most of these dykes at this locality were emplaced in a plane slightly oblique to the mylonitic foliation. Those at higher azimuth than the foliation are shortened, producing lozenge-shaped fragments (**Plate 2C**), while those disposed at lower azimuth are symmetrically boudined, being extended in their own plane. Veins are similarly affected. These relations suggest dextral shear combined with shortening across the shear plane. A compilation of kinematic indicators shows a mix of dextral and sinistral sense in the BSZ (Teklewold Ayalew and Moore, 1989); most of the dextral indicators are deformed mafic dykes. A sinistral sense of movement is identified at the Baro bend locality and elsewhere, from the displacement of late felsic dykes that clearly cut mylonitic foliation (**Plate 2D**), rotated feldspar augen, shear bands (**Plate 2E**) and folded mylonitic foliation (**Plate 1F**), all features of the later stages of deformation. The BSZ therefore appears to have been initiated with dextral movement and subsequently converted to sinistral movement, late in the strain history.

Varying degrees of mylonitization are observed in metaplutonic rocks of the BSZ. Shearing is most extreme in the Birbir quartz diorite complex, where rocks range from protomylonite to ultramylonite; rocks of the Goma and Mao plutons are protomylonitic. Mylonitic foliation and lineation are defined by quartz rods and hornblende and biotite aggregates. The Birbir quartz diorite sheets show a wide variety of grain sizes, grain boundary types and grain shapes on a very local scale. It is possible on the basis of petrographic studies to typify samples in order of increasing shear strain:

1) Protomylonites (**Plates 3A, B**; terminology follows Sibson, 1977): These rocks are medium to coarse grained, and although they are partly to largely recrystallized they contain well-preserved igneous textural features such as subhedral-euhedral plagioclase and hornblende phenocrysts, un-oriented biotite plates that tend to occur in clots, and perthite, antiperthite and myrmekite. Crystals are internally strained, but less than 10% of the rock consists of fine matrix derived by strain recovery from the primary crystals.

2) Mylonites (**Plates 3C, D and E**): These rocks display similar strain features to those described below but have subequal proportions of matrix (composed of quartz, feldspar, biotite, hornblende and epidote) and phenoclasts (plagioclase and hornblende). Granoblastic quartz and feldspar show undulatory extinction.

3) Mylonites and ultramylonites (**Plate 3F, G**): These are composed of a fine grained lepidoblastic matrix of quartz, feldspar and hornblende (10–20%). Plagioclase laths up to 5 mm are commonly bent and contain strain-induced albite and pericline twin lamellae. Some are mantled by very fine grained feldspars. Some of the plagioclase phenoclasts have recognizable "tails", formed by very fine-grained crystals, that can be used to determine the sense of shear. As biotite commonly substitutes about 15% of the rock, a large part of the strain imposed through shearing was probably taken up by grain boundary sliding. As a result, some hornblende and plagioclase phenoclasts were relatively unaffected and survived shearing. Shear foliation is mainly defined by alignment of biotite flakes and oriented hornblende and plagioclase phenoclasts, probably a result of rigid body rotation. Fine grained quartz and feldspar are polygonized and locally ribboned into strain-free grains that make up the bulk of the matrix. Deformation in these rocks seems to be essentially a product of ductile processes involving recrystallization and recovery.

Evidence for non-penetrative internal deformation in the Goma and Mao plutons is shown by narrow shear zones, that are especially well-developed near the contacts. Both ductile and brittle shear strain are seen in samples from the western contact of the Goma pluton. The strain features include undulose extinction in quartz and to a lesser extent in feldspars. Feldspar phenoclasts are mantled by fine grained recrystallized grains along weak deformation bands, and microfractures in plagioclase phenoclasts are filled by stringers of secondary minerals. The Mao pluton clearly transects the boundaries of several mylonitic units of the BSZ, also however shows brittle-ductile deformation near the margins, containing shear bands defined by quartz and mica ribbons, and bent and microfaulted feldspar porphyroclasts.

The three plutons that cut the Birbir-Baro domain boundary show no mesoscopic evidence of post-intrusion strain. In thin section the Bonga granite reveals internally strained quartz and feldspar, without recrystallization, showing that it postdates all but minor deformation.

Baro and Geba domains

Rocks of the Baro domain which contain planar structures with a general northerly strike and moderate dips to the east and west (Fig. 3) exhibits an incomplete foliation girdle. Linear features plunge gently north and south, except in an area immediately west of the Birbir domain at the northern end of the map area, where lineations plunge moderately toward the east and down the dip of foliation (Fig. 3). At that locality a fold pattern expressed by foliation is truncated; the abrupt change in foliation pattern coincides with changes in the attitudes of linear features. Intrafolial folds are locally recognized in migmatites. Foliation attitudes mapped west of Bonga and seen on aerial photographs define a major antiform with kilometre-scale wavelength and a north-south trending axial surface trace. Crenulation and weak mineral lineations are developed with gentle northerly plunges, parallel to the inferred axis of map area to the west, shows an upright, open fold pattern. Similar granite sheets are found to the south of the map area, and Davidson (1983) described them as having tectonic contacts related to thrusting. Undeformed granitoid pegmatites cut the main fabric of these rocks.

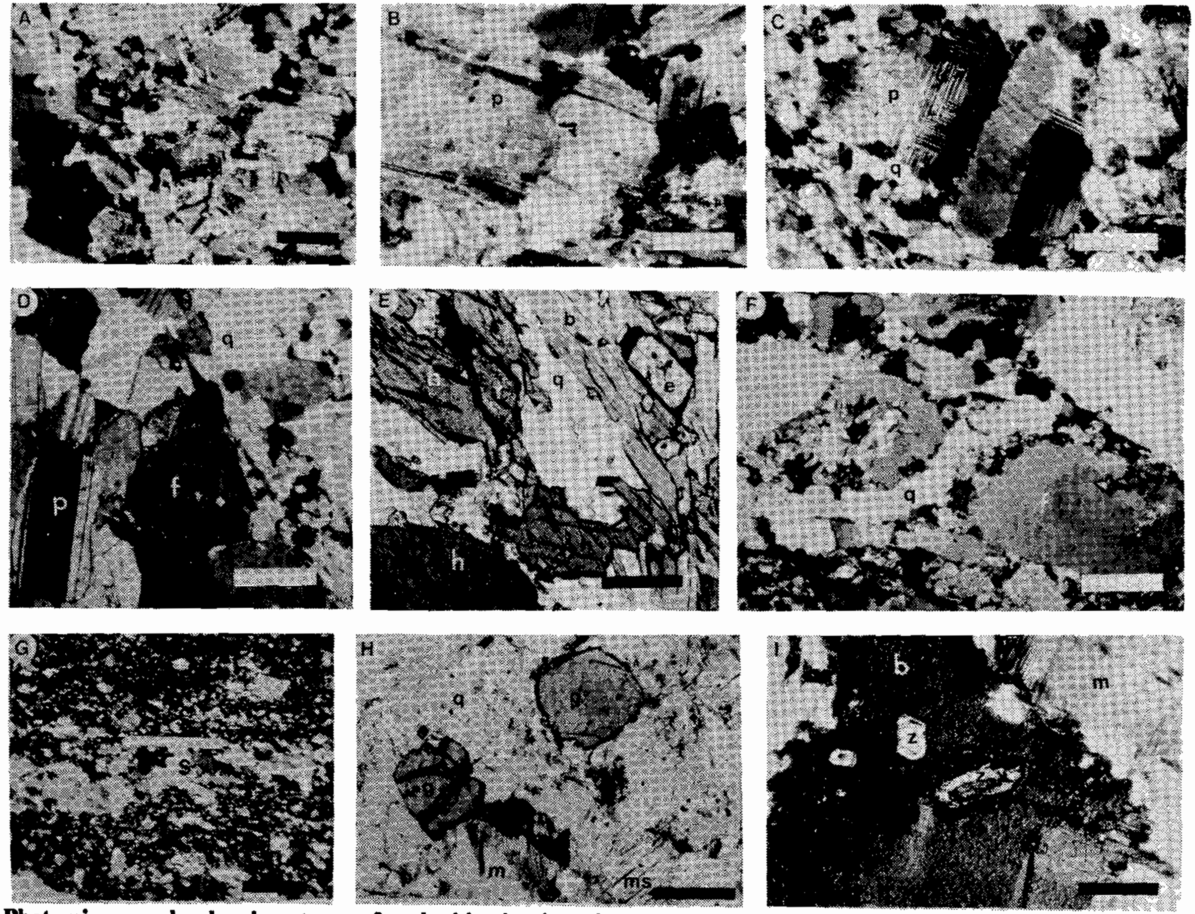

Plate 3. Photomicrographs showing stages of mylonitization in unit mqd in the Birbir shear zone (A to G) and some minerals and textures of granites. PPL=plane polarized light; XPL=under crossed polarizers. Scale bar is 1 mm for A and G and 0.5 mm for B to F, H and I. Bonga is shown on the Geological Map (Fig. 1). See next page for the notations A, B, C, D, E, F, G, H and I.

A, Subhedral-granular texture, showing curved to slightly embayed grain boundaries of plagioclase laths, unoriented biotite and hornblende, and interstitial quartz. XPL. Sample # T41.

B, Bent and kinked plagioclase (P) showing twin lamellae; micro-fractures and zones of sericitization run at right angles to the twin lamellae. XPL. Sample # T1H.

C, Plagioclase phenoclasts (P) showing deformation twins and subgrain development mantled by recrystallized quartz (q) and feldspar. XPL. Sample # T5G.

D, Granoblastic quartz (q) and feldspar (f) with plagioclase (p) phenoclasts showing straight grain boundaries and triple junctions. XPL. Sample # T3G.

E, Biotite (b) and hornblende (h), euhedral epidote (e), titanate (t), and interstitial quartz (q) defining mylonitic foliation. PPL. Sample # T5G.

F, Polygonized quartz ribbons (q) around K-feldspar porphyroclasts (f). Note that the feldspar shows drawn-out tails indicating dextral sense of shear. XPL. Sample # T8H.

G, C-S fabric shown by microcrystalline aggregates of recrystallized feldspar and quartz in >80% fine matrix. Shear foliation C is defined by traces of matrix layers. XPL. Sample # OY107, locality: 5 km northeast of the Baro - Birbir River confluence.

H, Garnet-muscovite granite of Baro Domain (mgt). g, garnet; ms, muscovite; m, microcline; q, quartz; p, plagioclase. PPL. Sample # T4M, locality: 7.5 km east of Bonga.

I, Large biotite crystals enclosing euhedral zircons (z) in Bonga granite (gt). m: microcline. XPL. Sample # T5K, locality 7 km east of Bonga.

Gneisses of the Geba domain also show open folding of the layering and foliation around gently plunging, NNE-trending axes, and shallow extension lineations (Fig. 3). The foliations dip predominantly toward the west. A major antiform at the western margin of the Geba domain has been truncated against rocks of the Birbir domain; the contact is marked by the mylonitic metagranite sheet (mgt). Farther east in the Geba domain, beyond the study area, a map-scale isoclinal recumbent folds with east-west oriented axial surface traces have been reported (Kazmin *et al.*, 1979; Mengesha Tefera and Seife Michael Berhe, 1987). These are deflected into a north-south trend as the boundary with the Birbir domain is approached. Reconnaissance during the present study shows that, in the same area, north-south folds are superimposed on flat lying gneissic layering. Early east-west folds have not been identified in the Baro domain.

At least two stages of ductile deformation can thus be documented in rocks of the gneissic terranes. The earlier is defined by a well-developed gneissic layering and penetrative mineral foliation, that locally encloses intrafolial folds, and may at least in the Geba domain be associated with the formation of east-west-trending folds. A second event resulted in kilometre-scale folds in the foliation of the earlier deformation.

Late brittle deformation

Numerous lineaments, mainly east-west-trending, are recognizable in the topography of the study area. A few of these are shown as faults (Fig. 1) because they clearly offset bedrock contacts and/or are occupied by brecciated zones; the nature of the others is more conjectural. The two most prominent lie in the north-central part of the area along much of the course of the Baro River. The enclosing rocks are brecciated and locally altered; blocks up to tens of metres across are variably rotated. Where indicated, movement is primarily dextral strike slip; offset of map units suggests up to 500 m lateral displacement.

Geochronology

The sequence of events is discussed in a separate paper elsewhere (Teklewold Ayalew *et al.*, 1990). Three ages of plutonism are identified in western Ethiopia, at *ca.* 830–810, 780 and 570–550 Ma. The earliest plutons intruded low amphibolite facies metasedimentary rocks in the Birbir domain that are unknown age, but the lithology of the clastics suggests affinity with calc-alkaline volcanism that was probably coeval with early plutonism (Teklewold Ayalew and Moore, 1989). Emplacement of the Baro leucogranite denotes a high-grade regional metamorphic event that is also probably reflected in resetting of Rb-Sr isotopic systems at ca. 760 Ma in the Birbir Domain. Metamorphism took place in the Birbir Shear Zone at 635 Ma and in the eastern Baro Domain at 580 Ma. Deformation and metamorphism in the western Ethiopian Shield had ceased by ca. 550 Ma.

Relative timing of deformation, plutonism and metamorphism

There is structural evidence of two distinct deformational events in each of the domains. In the Birbir domain, trends of early schistosity and near-parallel layering in metasedimentary schist (mss) are truncated by the Goma pluton along its northern contact. The pluton, in turn, is cut by mylonite zones and on its western side is truncated by the Birbir shear zone. The Bure metagabbro and Haya tonalite are in areas where mylonitization is not intense, so their fabrics probably date from the earlier deformation. It cannot be stated with certainty whether meta-quartz diorite (mqd) and other units in the BSZ have been affected by the earlier event. The main mylonitic zones of the BSZ are cut by the Mao granite, that is only slightly affected by later shearing. In the gneissic domains, foliation with intrafolial folds representing the earliest evident deformation is deformed around mesoscopic to map-scale folds. Baro leucogranite was involved in both deformations. Rocks of both the Birbir and Baro domains, and the boundary between them, are cut by essentially undeformed plutons including the Bonga granite.

The development of the major cleavage in rocks of the Birbir domain was followed by porphyroblastic growth. Pelitic rocks of the metasedimentary schist unit (mss) contain biotite, staurolite and andalusite porphyroblasts that overgrew the foliation and contain aligned inclusions that suggest that their growth post-dated the development of the major planar fabric. Hornblende and biotite also overgrew mylonitic schistosity in the Birbir shear zone. In the Baro domain, in garnet-sillimanite gneiss unit (gsg), some sillimanite occurs in knots elongated parallel to the foliation and a subhorizontal lineation, indicating syntectonic growth. However garnet porphyroblasts and some sillimanite (fibrolite) overgrew the fabric, suggesting that metamorphism outlasted regional deformation. Where mesoscopic folds in the gneissic foliation are observed, there is crenulation but minerals are not internally strained, implying that the metamorphic peak outlasted all major deformation. Isotopic data presented above ad elsewhere (Teklewold Ayalew *et al.*, 1990) indicate the existence of at least two metamorphic events.

CONCLUSION

The present study has revealed that the rocks of the Birbir domain are sheared throughout and also bounded by tectonites. The western margin of the Birbir domain contains a major shear zone; the eastern boundary is also marked by mylonite and by truncation of foliation patterns that define an antiform in the Geba domain. Deformation within the Birbir domain has produced penetrative foliation and schistosity that run parallel to those of the enclosing gneissic terranes. An apparently coeval regional deformation thus appears to have affected rocks of both the high-grade Baro and Geba and the lower-grade Birbir terranes.

Mineral assemblages in metasedimentary schists (mss) of the Birbir domain indicate low pressure-medium temperature metamorphism of the lower amphibolite facies, whereas sillimanite-K feldspar-orthoamphibole assemblages to the west indicate medium pressure-high temperature metamorphism of upper amphibolite facies. The change in metamorphic grade is observed in samples obtained within strike-normal distances of 1–4 km, suggesting abrupt increase in metamorphic grade across the boundaries of the Birbir domain. The metamorphic gradient is probably too steep to be accounted for by exposure of more deeply buried rocks by tilting, and there are no faults in the area that appear to have major vertical displacements. The two domains thus appear to have been tectonically juxtaposed.

Older east-west-oriented folds documented in gneisses of the Geba valley, beyond the study area, have not been seen in the Baro domain. Along the north-west frontier between Ethiopia and the Sudan, however, Warden and Horkel (1984) identified east-west trending folds from satellite imagery. There is little evidence to correlate the Baro and Geba domains, but the presence in both of more than one generation of deformation, similar grade of metamorphism are composed of reworked rocks, possibly pre-Pan African in age. Intense deformation along north-south Pan-African structures, coupled with recrystallization, may have obliterated any earlier metamorphic features.

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