Tectonothermal history of the Mesoproterozoic Novillo Gneiss of eastern Mexico: support for a coherent Oaxaquia microcontinent

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ABSTRACT

The Novillo Gneiss is one of several exposures of Mesoproterozoic (ca. 1.0–1.2 Ga) basement in eastern Mexico interpreted to be outcrops of a single crustal block (Oaxaquia) that has figured prominently in continental reconstructions for the late Precambrian-Paleozoic. Exposed within the Sierra Madre Oriental near Ciudad Victoria, the Novillo Gneiss comprises two major Mesoproterozoic igneous suites that intrude rare metasedimentary rocks. The older suite, previously dated at 1235–1115 Ma, principally comprises garnet K-feldspar augen gneiss and granite gneiss with arc/back-arc geochemical affinities. The younger suite (charnokitic gneiss, anorthositic metagabbro) has been dated at 1035–1010 Ma and is interpreted to be part of an anorthosite-mangerite-charnockite-granite assemblage. Both suites are intruded by two sets of amphibolite dikes, the earlier of which predates metamorphism under granulite facies conditions at ca. 990±5 Ma, whereas the later set is of low grade and was emplaced at ca. 546 Ma.

New structural data in both major igneous suites are dominated by the presence of a composite NW-trending, steeply dipping metamorphic banding/foliation (S_1) axial planar to rare isoclinal folds, and a lineation defined by stretched, 12:2:1, K-feldspar augen and quartz ribbons developed under high-grade metamorphic conditions. The irregular contacts between leucosome and mesosome boundaries may be a remnant of earlier, pre-S_1 migmatization. These are overprinted by tight-isoclinal F_2 sheath folds associated with a moderately ESE-plunging clinopyroxene mineral lineation that bisects the great circle distribution of S- and Z-shaped asymmetrical F_2 fold axes, indicating oblique sinistral, top-to-NW relative movement. The L_1 lineations also have a great circle distribution suggesting that inhomogeneous stretching in the foliation rotated L_1 towards L_2. Syntectonic fabrics are overprinted by a granoblastic granulite facies mineralogy followed by retrograde amphibolite and greenschist facies fabrics, the latter associated with the fault that juxtaposes the Novillo Gneiss and the Paleozoic Granjeno Schist. A ca. 350 Ma leucogranite intruded along this fault was deformed at ca. 313 Ma. This tectonothermal history is closely comparable to that of the Oaxacan Complex (southern Mexico), supporting the existence of a coherent Oaxaquia. The absence of the later amphibolite dikes in the Oaxacan Complex likely reflects its relative paleogeography at the time of dike emplacement.

Key words: Novillo Gneiss, Oaxaquia, Mesoproterozoic, Oaxacan Complex, Mexico.

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RESUMEN

El Gneis Novillo es uno de los varios afloramientos de basamento Mesoproterozoico (ca. 10-1.2 Ga) en el este de México que han sido interpretados como pertenecientes a un único bloque cortical (Oaxaquia), el cual ha figurado de manera prominente en las reconstrucciones continentales del Precámbrico tardío-Paleozoico. Aflorando en la Sierra Madre Oriental, cerca de Ciudad Victoria, el Gneis Novillo consta de dos suites ígneas mesoproterozoicas mayores que intruyen escasas rocas sedimentarias. La suite más antigua, fechada previamente en 1235–1115 Ma, consiste principalmente de augen gneis de granate y feldespato potásico con afinidad geoquímica de arco/retroarco. La suite más joven (gneis charnokítico, metagabro anortosítico) ha sido fechada en 1035–1010 Ma y se interpreta como parte de un ensamble de anortosita-mangerita-charnockita-granito. Ambas suites son intruidas por dos conjuntos de diques anfibolíticos, de los cuales el más temprano antecede al metamorfismo en condiciones de facies granulíticas fechado en ca. 990±5 Ma, mientras que el conjunto más tardío es de bajo grado y se emplazó a ca. 546 Ma.

Nuevos datos estructurales de ambas suites ígneas mayores indican que predomina la presencia de bandeamiento/foliación (S_1) metamórfico de plano axial con rumbo NW e inclinación de ángulo alto con escasos pliegues isoclinales; la lineación está definida por feldespato potásico y listones de cuarzo alargados, 12:2:1, desarrollada bajo condiciones metamórficas de alto grado. Los contactos irregulares de las fronteras entre el leucosoma y el melanosoma pueden ser un remanente de migmatización más temprana, pre-S_1. Estos son sobrepuestos por 'sheath folds' isoclinales cerrados F_2, asociados con una lineación mineral de clinopiroxeno con buzamiento moderado al ESE que bisecta las distribuciones de las guirnaldas de los ejes de pliegues asimétricos F_2 con forma S y Z, indicando movimiento relativo oblicuo sinestral con movimiento de las capas del techo hacia el NW. La distribución de las guirnaldas de las lineaciones L_1 sugiere un alargamiento inhomogéneo que rotó la foliación L_1 hacia L_2. Las fábricas sintectónicas son sobrepuestas por una mineralogía granoblástica de facies granulítica seguida por fábricas retrógradas de facies de anfibolita y esquistos verdes, la última asociada con la falla que yuxtapone al Gneis Novillo con el Esquisto Granjeno del Paleozoico. Un leucogranito de ca. 350 Ma, que intruyó a lo largo de esta falla, fue deformado a ca. 313 Ma. Esta historia tectonotérmica es muy parecida a la del Complejo Oaxaqueño (sur de México), apoyando la existencia de una Oaxaquia unida. La ausencia de los diques anfibolíticos tardíos en el Complejo Oaxaqueño probablemente refleja su paleogeografía al tiempo del emplazamiento de los diques.

Palabras clave: Gneis Novillo, Oaxaquia, Mesoproterozoico, Complejo Oaxaqueño, México.

INTRODUCTION

The Novillo Gneiss is one of four outcrops of *ca.* 1.0–1.2 Ga rocks in eastern Mexico (Figure 1) that are interpreted to represent isolated exposures of an extensive Mesoproterozoic basement. Although separated by as much as 700 km, these gneisses (the Novillo Gneiss, Huiznopala Gneiss, Guichicovi Gneiss and Oaxacan Complex) have a number of features in common, including pervasive granulite facies metamorphism, abundant anorthositic complexes, and a NW-trending structural orientation, in addition to their age (Ortega-Gutiérrez, 1978; Lawlor *et al.* 1999; Weber and Köhler, 1999; Keppie *et al.*, 2001, 2003; Solari *et al.*, 2003; Weber and Hecht, 2003; Cameron *et al.*, 2004; Keppie and Ortega-Gutiérrez, 2010; Weber *et al.*, 2010).

Early workers considered this basement to be an extension of the *ca.* 1.0–1.2 Ga Grenville orogen of eastern Laurentia (*e.g.*, de Cserna, 1971; Denison *et al.*, 1971; Shurbet and Cebull, 1987). However, paleomagnetic data (Ballard *et al.*, 1989) and faunal evidence (Robison and Pantoja Alor, 1968; Rowley and Pindell, 1989; Stewart *et al*., 1993) proved inconsistent with this connection and, instead, favored correlation with Gondwana. On this basis, Ortega-Gutiérrez *et al.* (1995) suggested the basement was part of a microcontinent they termed 'Oaxaquia', which originated near Gondwana in the early Paleozoic and was only accreted to Laurentia during the late Paleozoic assembly of Pangea. Oaxaquia was inferred to extend from northern Mexico to Central America, a distance of some 2000 km, making it a major segment of the worldwide belt of Mesoproterozoic ("Grenville-age") orogenesis.

Correlation based on Pb isotope data, however, has been equivocal. Ruiz *et al.* (1999) provided whole-rock data that suggested the northernmost exposure of Oaxaquia (the Novillo Gneiss) isotopically resembled gneisses of the Laurentian Grenville belt in Texas, whereas the Mesoproterozoic gneisses of southern Mexico (the Huiznopala Gneiss, Oaxacan Complex and Guichicovi Gneiss) were isotopically similar to those of the Colombian Andes. This mandated a suture between the Novillo Gneiss and the Huiznopala Gneiss and, hence, brought into question the concept of the Oaxaquia microcontinent. However, Cameron *et al.* (2004) showed the northern and southern exposures to have similar isotopic signatures based on leached feldspar data, lending support to the concept of a

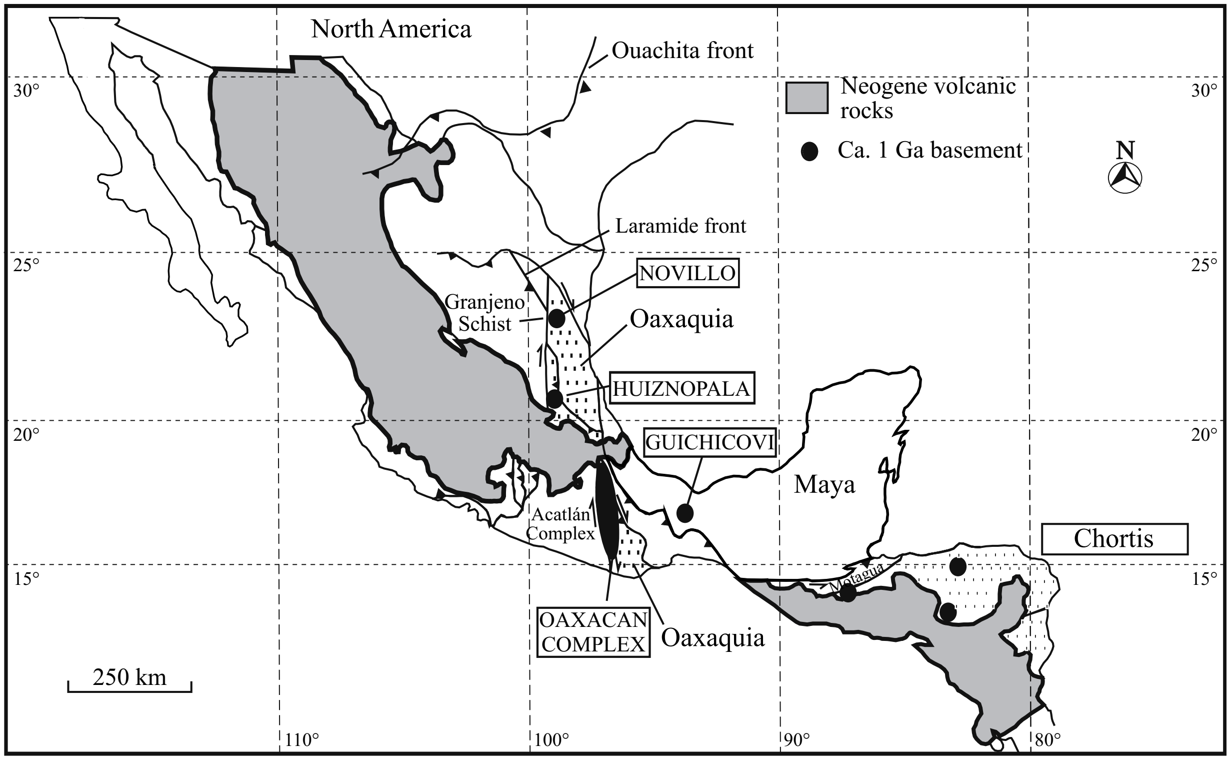

Figure 1. Map of Mexico and northern Middle America showing locations where Mesoproterozoic (*ca.* 1.2–1.0 Ga) basement (black) is exposed (Novillo Gneiss, Huiznopala Gneiss, Oaxacan Complex, Guichicovi Gneiss) or has been encountered in drill holes, and the proposed extent (coarse stippled pattern) of the microcontinent Oaxaquia (simplified from Keppie and Ortega-Gutiérrez 2010). Fine stippled pattern: Chortis block.

single crustal block, a conclusion since supported by the Hf isotope data of Weber *et al.* (2010).

To clarify this uncertainty, we present the results of a structural-kinematic and petrographic analysis of the Novillo Gneiss (Trainor, 2010), which we combine with published age data in order to establish a tectonothermal history. We then compare this history with that of the better-known Oaxacan Complex (Keppie *et al.*, 2001, 2003; Solari, *et al.*, 2003) to the south, the Gondwanan affinities of which are well documented (Landing *et al.*, 2007; Streng *et al.*, 2011). The results support the coherence of Oaxaquia, the existence of which has figured prominently in continental reconstructions for the late Precambrian (*e.g.*, Dalziel, 1997; Li *et al.*, 2008; Scotese, 2009; Weber *et al.*, 2010) and is central to plate tectonic models for Gondwana-Laurentia in the Paleozoic (*e.g.*, Keppie *et al.*, 1996, 2008; Keppie and Ramos, 1999).

GEOLOGIC SETTING

The Mesoproterozoic (*ca.* 1.0–1.2 Ga) Novillo Gneiss of northeastern Mexico outcrops in the core of the Huizachal-Peregrina anticlinorium (Figure 2), a large NW-trending Laramide structure located in the front ranges of the Sierra Madre Oriental west of the city of Ciudad Victoria (Ramírez-Ramírez, 1974, 1992; Ortega-Gutiérrez, 1978). Occupying an area of about 35 km^2, the complex comprises a succession of consistently NE-dipping units that includes an intrusive anorthosite-mangerite-charnockite-granite (AMCG) suite that is flanked to the northeast and southwest by a suite of older orthogneisses and rare metasedimentary rocks (Figure 3). Both suites are intruded by mafic dikes of two generations and are overlain by a Paleozoic cover succession.

The Novillo Gneiss is tectonically juxtaposed to the west against low-grade Paleozoic rocks of the Granjeno Schist (Figure 2), which make up part of the Sierra Madre terrane. This polydeformed assemblage of metasedimentary and metavolcanic rocks, and serpentinized mafic-ultramafic units is interpreted to be an oceanic accretionary prism possibly associated with the Late Paleozoic closure of the Rheic Ocean (Dowe *et al.*, 2005; Nance *et al.*, 2007). A leucogranite with a poorly constrained U-Pb zircon age of 351±54 Ma (Dowe *et al.*, 2005) has been emplaced into the fault zone separating the Granjeno Schist from the Novillo Gneiss.

To the east, the Novillo Gneiss is unconformably overlain by an unmetamorphosed Paleozoic (Silurian-Permian) sequence of marine clastics (Stewart *et al.*, 1999). In ascending order, this sequence includes: (1) Silurian conglomerate, silicic volcanic arenite, limestone, sandstone and siltstone, the latter containing marine fauna of Gondwana affinity, (2) Lower Mississippian shallow-marine, quartz and lithic

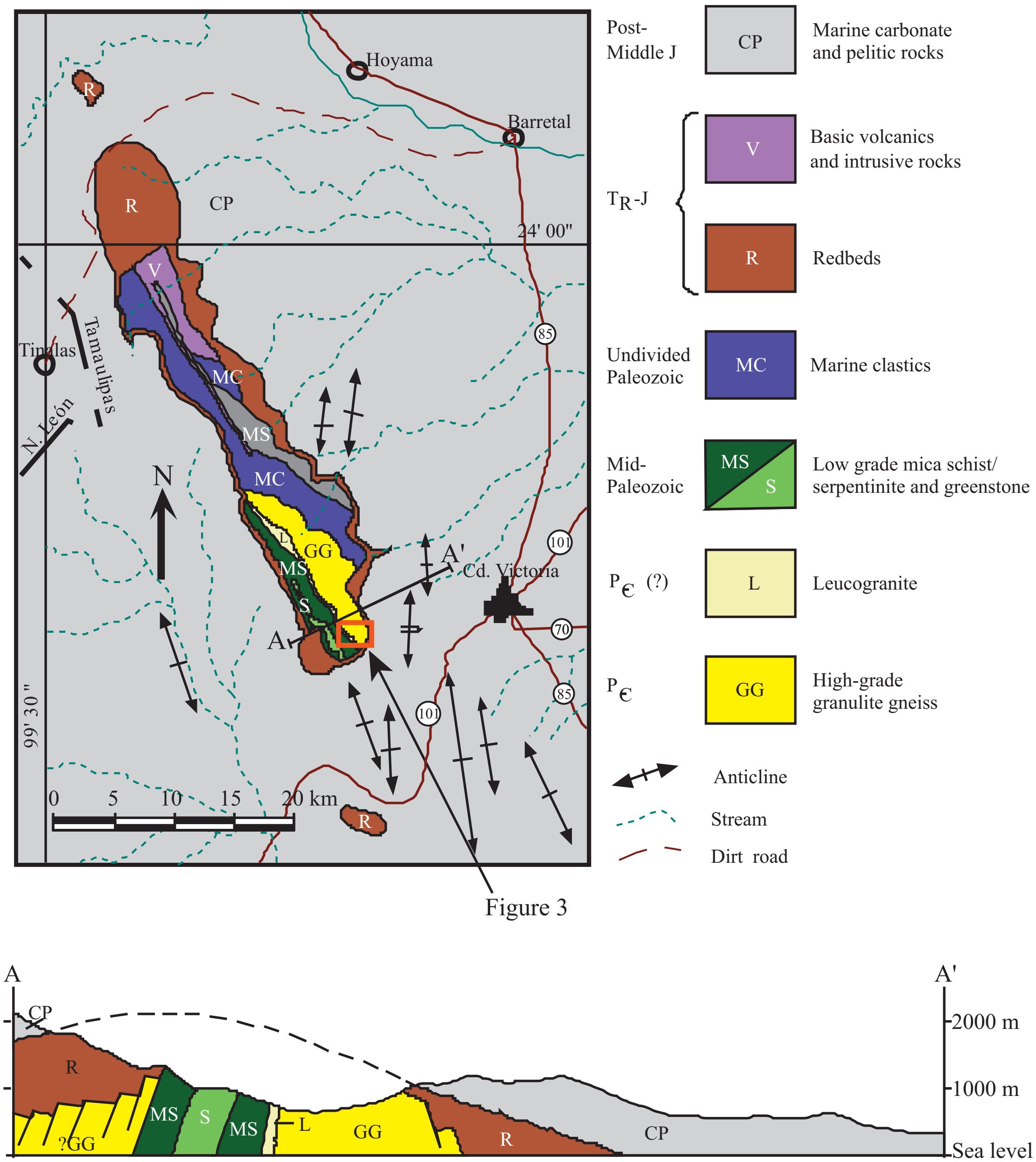

Figure 2. Geological map and cross section (along line A-A') of the Huizachal-Peregrina anticlinorium. Pre-Mesozoic units are exposed in the core. Red square shows location of Figure 3 (modified from Ramírez-Ramírez, 1992).

arenite, siltstone and shale containing Laurentian fauna, (3) Mississippian rhyolite, (4) an unconformably overlying Lower and Middle Pennsylvanian unit consisting of bioclastic grainstone, sandstone, and limy sandstone, and (5) a lower Permian unit consisting of turbiditic siltstone and sandstone rich in volcanic detritus. The Paleozoic succession is unconformably overlain by Mesozoic (Lower Jurassic-Cretaceous) conglomerate, limestone, siltstone and sandstone. Cretaceous-Early Cenozoic thin-skinned tectonics (Laramide orogeny) have deformed the Mesozoic sequence above the Jurassic, folding and displacing the overlying strata along NE-directed thrusts (Zhou *et al.*, 2006).

THE NOVILLO GNEISS

Geochronology

U-Pb zircon dating has shown that the Novillo Gneiss is composed of two major Mesoproterozoic igneous suites (Cameron *et al.*, 2004) that intrude rare metasedimentary (calc-silicate) units. The older suite is dated at 1235–1115 Ma and principally comprises garnet K-feldspar megacrystic metagranites and granite gneisses with arc/back-arc geochemical affinities (Cameron *et al.*, 2004). The second suite, dated at 1035–1010 Ma, is composed of

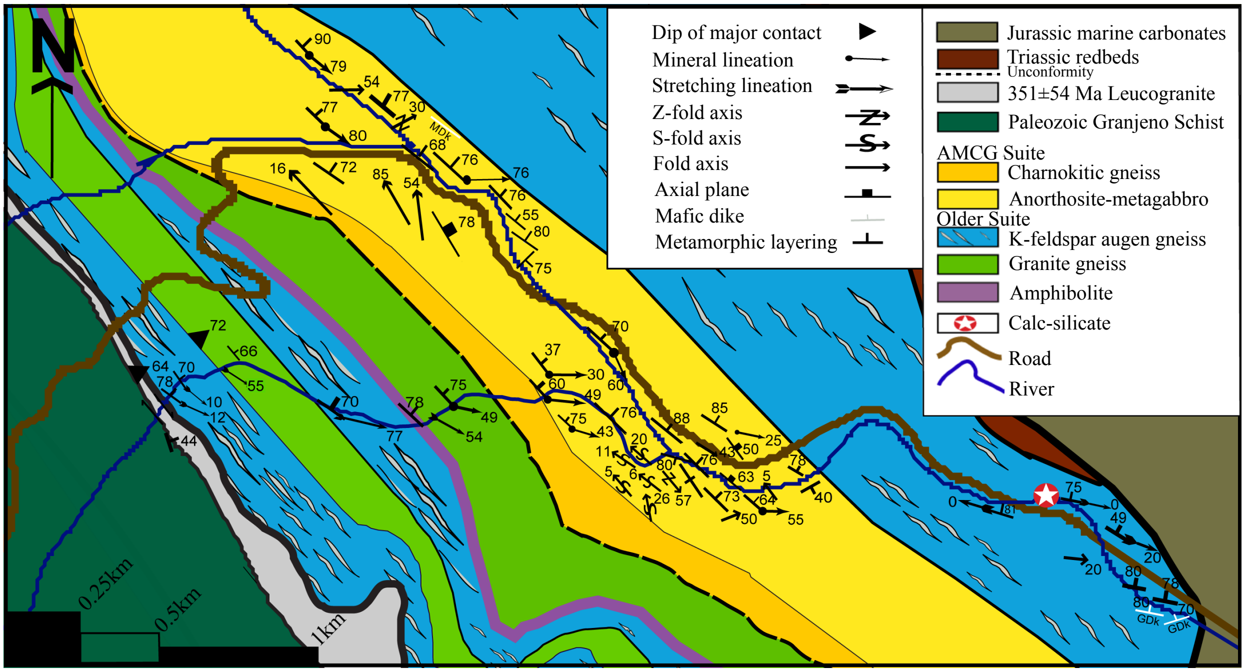

Figure 3. Geological map of the study area in the Cañón Novillo. Abbreviations: Pε = Precambrian, T_R = Triassic, J = Jurassic.

charnokitic gneiss and anorthositic metagabbro interpreted to be part of an AMCG suite (Cameron *et al.*, 2004). Both suites were intruded by a set of mafic dikes prior to being metamorphosed under granulite facies conditions dated at *ca.* 990±5 Ma on the basis of metamorphic zircon growth (Cameron *et al.*, 2004). Peak values for metamorphic pressure and temperature have been estimated at 8.9–9.7 kbar and 730–775 °C (Orozco, 1991).

A second set of low-grade mafic dikes intrudes all units of the Novillo Gneiss and has yielded a hornblende $^{40}Ar/^{39}Ar$ plateau age of 546±5 Ma that is considered to closely post-date their emplacement (Keppie *et al.*, 2006). The geochemical signature of the dikes suggests an intraplate magmatic source that these authors link, either to a mantle plume, or to decompression melting during passive asthenospheric mantle upwelling associated with lithospheric extension.

A cooling history for the Novillo Gneiss was estimated by Keppie *et al.* (2006) on the basis of a U-Pb titanite age of 928±2 Ma and a $^{40}Ar/^{39}Ar$ biotite age of 697±10 Ma from a paragneiss. These data suggest that, following granulite facies metamorphism, the Novillo Gneiss cooled from ~660 °C (closure temperature for U-Pb in titanite; Frost *et al.*, 2000) to 325±25 °C (closure temperature for $^{40}Ar/^{39}Ar$ in biotite; Harrison *et al.*, 1985) in *ca.* 230 Ma, a cooling rate of ~1.45 °C/my.

Petrography and textures

Our mapping shows the bulk of the Novillo Gneiss to consist of variably retrogressed granulite facies felsic and mafic orthogneisses. These include garnet K-feldspar augen gneiss and granite gneiss in the older suite, and charnokitic gneiss and anorthositic-metagabbro units in the younger AMCG suite. Both suites are strongly layered, but whereas the AMCG suite shows continuous, well-defined, rhythmically alternating leucocratic-mesocratic layers, layering in the older suite is discontinuous and defined by variably stretched and flattened quartzofeldspathic augen (mm-cm in diameter) in a darker foliated matrix. The layering consistently strikes NW and dips SE (Figure 3). Rare calc-silicate units within the older suite are largely massive. Most ferromagnesian minerals show variable alteration to chlorite. The mineralogy is summarized in Table 1.

Metasedimentary rocks

Rare outcrops of massive calc-silicate in the older igneous suite comprise granoblastic carbonate, euhedral diopside, altered scapolite/wollastonite (with grossular garnet coronas) and recrystallized quartz ribbons.

Older Igneous Suite

A large portion of the older suite comprises monzonitic, garnet K-feldspar augen gneiss with a prominent blastomylonitic layering. Elongate, asymmetric to symmetric K-feldspar augen make up the bulk of the leucocratic (granoblastic microcline-plagioclase-quartz) layers, which are separated by thinner mesocratic bands comprising garnet strings, recrystallized quartz ribbons and pyroxene partially retrogressed to chlorite (Figure 4a).

The granite gneiss of the older suite is granodioritic in composition and shows stromatic leucosome-

Table 1. Mineralogy of the major units of the Novillo Gneiss.

Rock type	Microcline	Plagioclase	Quartz	Garnet	Pyroxene	Opaque	Other
AMCG unit (1035–1010 Ma)							
Charnokitic gneiss	30%	34%	13%	11%	9% (opx)	3%	chl
Anorthositic-metagabbro		75%	<5%	10%	<5% (cpx)	5%	chl
Older igneous unit (1235–1115 Ma)							
Granite gneiss	35%	30%	25%	17%			chl
Garnet K-feldspar augen gneiss	40%	25%	9%	23%	3%		
Mafic dikes		30%	20%	20%	20%	10%	act/chl
Garnet amphibolite		30%	20%	20%	20%	10%	act/chl
Porphyritic amphibolite (546 Ma)					rare	5%	hb (40%)/chl
Metasediment rocks							
Calc-silicate		carbonate, diopside, scapolite/wollastonite + grossular garnet corona, quartz					

Abbreviations: act = actinolite, chl = chlorite, cpx = clinopyroxene, hb = hornblende, opx = orthopyroxene.

mesosome segregation layering with indistinct layer boundaries. The banding is folded into tight, highly irregular, asymmetric folds on a mm-cm scale (Figure 4b). The leucosome comprises approximately equal proportions of granoblastic microcline, plagioclase and rutilated quartz, the latter defining conspicuous recrystallized ribbons that are occasionally isoclinally microfolded. The mesosome contains additional euhedral garnet clusters concentrated along layer boundaries and minor chlorite after pyroxene.

AMCG Suite

The younger AMCG suite includes strongly layered charnokitic gneiss and anorthositic-metagabbro, but is so pervasively recrystallized to a granoblastic texture (charnokitization) that structures are more easily observed macroscopically than microscopically. Layering in the charnokitic gneiss (Figure 4c) is the result of varying proportions of the same mineralogy, the composition of which is generally monzonitic. Orthopyroxene is usually retrogressed to chlorite, but its presence makes the rock mangeritic or charnokitic.

Layering in the anorthositic-metagabbro is exceptionally coherent, often forming continuous bands across entire outcrops (Figure 4d). The mineralogy is dominated by plagioclase with minor garnet, clinopyroxene (variably altered to chlorite), quartz and opaques, with the darker layers containing more abundant garnet. The layers are cut by veinlets of nelsonite (ilmenite and apatite).

Mafic Dikes

Both suites of orthogneisses are cut by two sets of mafic dikes, the first comprising relict garnet amphibolites, whereas the second comprises porphyritic amphibolite. The older garnet amphibolite dikes are foliated metabasites and range in width on a cm-meter scale. These metabasites are finely laminated with dark green, strongly altered mesocratic layers dominated by fine chlorite (after amphibole and pyroxene) and thin leucocratic laminae containing highly elongate plagioclase lenses and recrystallized quartz ribbons (Figure 4e). The laminations are often strongly folded and cataclastically deformed. A granoblastic texture overprints the foliation defined mainly by garnet-rich bands, but a granulite facies mineralogy is no longer preserved.

The younger porphyritic amphibolites are undeformed hornblende-andesites with chilled margins and widths on a dm-meter scale. They display an ophitic texture with randomly oriented plagioclase phenocrysts. The hornblendes contain rare pyroxene cores and are variably replaced by chlorite.

Structure and metamorphism

The AMCG suite occurs as a tectonic slice within the older gneisses; to the west, the *ca.* 351 Ma leucogranite forms a fault sliver between the Novillo Gneiss and the Granjeno Schist, and to the east, Mesozoic rocks are in fault contact with the Novillo Gneiss (Figure 3). A similar fourfold tectonothermal history is recorded in the older gneisses, the AMCG unit and the garnetiferous dikes (Table 2). The first two events post-date emplacement of the AMCG suite at 1035–1010 Ma, but predate granulite facies metamorphism at *ca.* 990 Ma, the third coincides with this metamorphism, and the fourth post-dates it. The *ca.* 546 Ma porphyritic mafic dikes post-date all these events.

First event

The dominant fabric in all the rocks is a compositional banding and foliation, S_1, with alternating leucocratic (quartzofeldspathic) and mesocratic layers that are interpreted to be a result of high-grade metamorphic differentiation. In places in the granite gneiss, the banding is irregular and stromatic, and is interpreted to be an earlier,

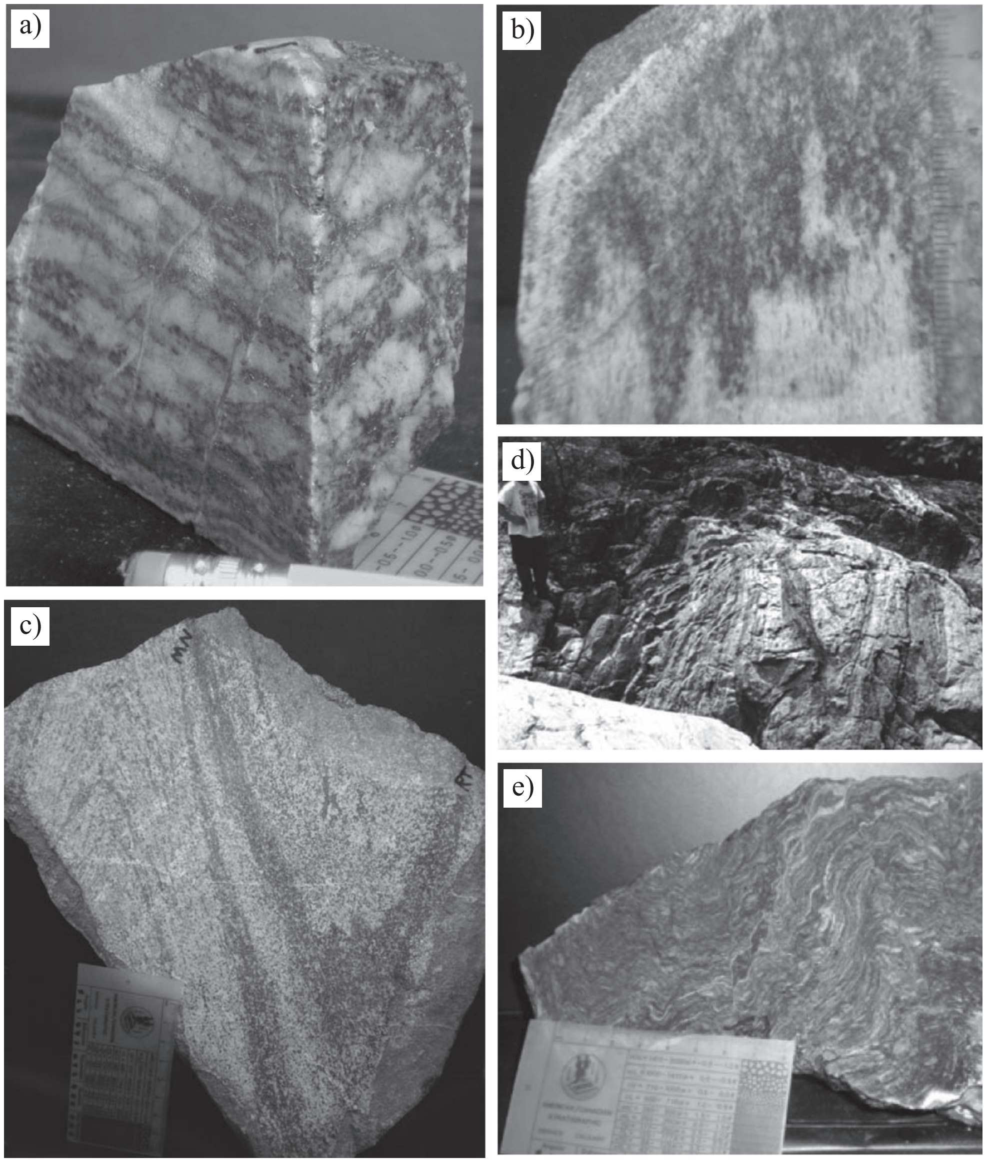

Figure 4. Representative photographs of (a) megacrystic K-feldspar augen gneiss, (b) migmatitic granite gneiss, (c) charnokitic gneiss, (d) anorthositic-metagabbro in the AMCG suite, and (c) retrogressed amphibolite in the older suite.

pre-S_1, migmatitic feature: this is consistent with garnet concentrations along the borders of quartzofeldspathic leucosome layers resembling migmatite resisters (Winkler, 1979). Rare tight-isoclinal folds in the banding have axial planes defined by S_1. In the AMCG suite, the S_1 foliation is axial planar to tight to isoclinal intrafolial folds that are variably oriented within the steeply NE-dipping, S_1 foliation (Figure 5a). The pole to the S_1 foliation plunges gently SW (statistically at $15^o/218^o$). In the older suite, a prominent lineation, L_1, consisting of stretched K-feldspar augen and quartz ribbons is variably oriented within the S_1 foliation (Figure 5b). In the K-feldspar augen gneiss, the augens are up to 10 cm long and flattened parallel to a weak, steeply NE-dipping foliation developed in the mesocratic layers. Although such fabrics can develop under conditions ranging from greenschist to granulite facies (Passchier and Trouw, 1996; Levine and Mosher, 2010), deformation of the augen requires temperatures above the brittle-ductile transition in feldspar at ~500^{o}C. The augen are of prolate shape with orientations and length to width to height ratios (X:Y:Z = 12:2:1) that are similar to those of the quartz ribbons. No clear sense of shear is evident in the augen.

Second event

The second tectonothermal event in the AMCG unit is recorded by tight to isoclinal, occasionally rootless, asymmetric, Class 1C-3 folds (F_2), which lack an axial planar fabric and locally refold F_1 (Figure 6). Plotted stereographically (Figure 5c), F_2 axes are distributed about a great circle, the pole to which plunges gently SW. An associated clinopyroxene mineral lineation (L_2) plunges moderate-steeply ESE and suggests continued high-grade

Table 2. Correlation chart of tectonothermal events within major units of the Novillo Gneiss.

Tectonothermal event	**Older gneisses (1235–1115 Ma)**	**AMCG unit (1035–1010 Ma)**	**Garnet amphibolites**
? Amphibolite facies	?Migmatization		
1. Upper Amphibolite-Granulite facies	Metamorphic banding and foliation (S_1)		
	Quartz ribbons (L_1) Stretched K-feldspars	F_1 isoclinal folds Axial planar foliation (S_1)	
2. Granulite facies	Rotation of ribbons and augen	Sheath folds (F_2) Sinistral-reverse thrusting Clinopyroxene lineation (L_2)	SE-plunging fold
3. Granulite facies static metamorphism	Granoblastic crystal growth		
4. Greenschist facies	Steeply inclined NW-SE, SE-plunging folds (F_3)		
5. Faulting	Dextral shear faults and brittle fractures		

metamorphic conditions. The distribution of fold asymmetries (*i.e.*, S and Z folds) is consistent with sheath folding. From exposed sheath fold patterns, the 'noses' of which can be used to indicate the direction of transport, folding was the result of sinistral thrusting towards the WNW, parallel to L_2. In the older suite, a second planar fabric (S_2) is developed axial planar to isoclinal intrafolial microfolds in the metamorphic layering, although both planar fabrics are extensively retrogressed. The quartz ribbons are also locally deformed by isoclinal folds. These folds are gently ESE-plunging and have a nearly ideal Class 2 geometry. The long axes of the augen and quartz ribbons in the older gneisses (Figure 5b) also show a similar great circle distribution to that of the isoclinal, F_2 fold axes in the AMCG unit (Figure 5c), suggesting that the distribution of the stretching lineation also results from rotation towards the L_2 mineral lineation. The absence of an S_2 axial planar fabric in the AMCG suite may be due to its massive nature and further development (enhancement) of the S_1 foliation.

The garnet amphibolite dikes cut the S_1 foliation in the AMCG suite, but are themselves foliated and locally deformed about mesoscopic F_2 folds.

Third event

The first and second fabrics are pervasively overprinted by granoblastic textures in the gneisses, such that the rocks show no significant strain within either the grains or ribbon structures. This indicates recrystallization under conditions of static metamorphism, the accompanying mineral parageneses of which (orthopyroxene, clinopyroxene and garnet) are indicative of the granulite facies. Because of this, determination of the metamorphic grades of earlier tectonothermal events is difficult.

Fourth event

The final structural/metamorphic event is evident in the development of subgrains and undulose extinction within the granoblastic quartz grains of all lithologies. In the garnet amphibolite dikes, retrograde mineralization and microfracturing associated with this event produced grain-size reduction, 'birds eye' feldspars and extensive chloritic retrogression along planes of displacement (S_3) that are axial planar to asymmetric F_3 folds in both S_1 and S_2. These folds (Figure 4e) are open, dm-scale SW-vergent structures with axes that plunge moderately to steeply SE and an axial planar fabric (S_3) that dips steeply NE. Offsets along S_3 point to a fold mechanism involving oblique shear with a subordinate component of flexural slip indicated by minor cataclastic deformation between compositional layers. The line of movement (perpendicular to the fold axis in the axial plane) plunges moderately northwest (Figure 5d), which in combination with the sense of fold vergence, indicates oblique shear with dextral and reverse components. The majority of microfracture offsets and associated slickensides also indicate dextral shear, consistent with dextral, SW-vergent thrusting.

Faulting

The porphyritic amphibolite dikes display no microdeformational strain features but, instead, preserve original ophitic igneous textures overprinted by retrograde (greenschist facies) mineralization indicating that their intrusion was shallow and post-dated all major ductile deformation. Evidence of chilled contacts also indicates that both the older and AMCG suites were at low temperatures when the dikes were emplaced. Some brittle movement is evident along dike contacts, and the dikes are locally offset by minor brittle faults, the majority showing dextral sense. This episode of retrogression must post-date dike intrusion at *ca.* 546 (Keppie *et al.*, 2006) and is thought to record dextral juxtapositioning of the Novillo Gneiss against the Granjeno Schist (Dowe *et al.*, 2005).

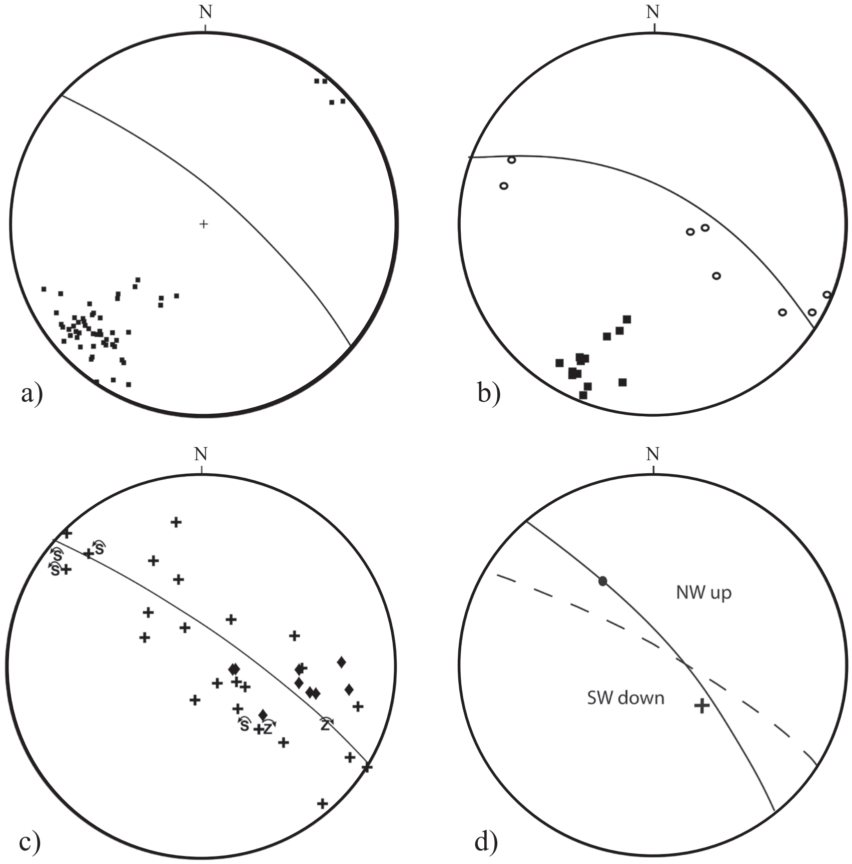

Figure 5. Equal area stereographic projections of (a) poles to foliation (S_1, solid squares – average orientation shown by great circle) in the AMCG suite, (b) poles to foliation (S_1, solid squares – average orientation shown by great circle) and long axes of augen (L_1, open circles) in K-feldspar augen gneiss in the older suite, (c) F_2 axes (crosses) and L_2 mineral lineations (solid diamonds) in the AMCG suite, and the steeply NE-dipping great circle about which they are distributed. Fold asymmetries shown by curved arrows over S and Z symbols, and (d) fold axis (cross), axial plane (solid great circle) and line of movement (solid circle) for F_3 fold in garnet amphibolite (dashed great circle shows composite S_1/S_2).

DISCUSSION

Evolution of the Novillo Gneiss

Based on this tectonothermal record, the Novillo Gneiss is interpreted to record the following history:

(1) Available age and geochemical data (Cameron *et al.*, 2004) show the older suite to have been emplaced between *ca.* 1235 and 1115 Ma in an arc or back-arc setting. Emplacement of the older gneisses may have been accompanied by migmatization, indicating high-grade metamorphism – the development of stromatic migmatites requiring temperatures of ~700–720°C (Winkler, 1979). Using a 30 °C/km geothermal gradient typical of active continental margins, such migmatization would have required depths of ~25 km.

(2) Emplacement of the AMCG suite occurred between 1035 and 1010 Ma (Cameron *et al.*, 2004).

(3) High-grade deformation producing two sets of structures in both the older gneisses and the AMCG suite involving the development of a metamorphic differentiation banding/foliation, isoclinal folds, and a 12:2:1 stretching lineation. These were overprinted by sheath folding with sinistral-reverse movement parallel to an ESE-plunging clinopyroxene lineation under high-grade metamorphic conditions. The garnetiferous mafic dikes cut across the earliest foliation but are themselves deformed by two sets of structures suggesting syntectonic intrusion.

(4) Granulite facies metamorphism (orthopyroxene-clinopyroxene-garnet) replaced all pre-existing microfabrics by granoblastic textures. The time of peak metamorphism has been dated at 990±5 Ma on the basis of metamorphic zircon growth (Cameron *et al.*, 2004). Preservation of the pre-existing quartz ribbons suggests that the pervasive recystallization was essentially static. The P-T conditions of this event have been estimated to be 8.9–9.7 kbar and 730–775°C (Orozco, 1991), the tectonic setting needed to produce the required ~40 km of burial likely being that of the roots of an orogenic belt developed during subduction or collision (*e.g.*, Jamieson *et al.*, 1998).

(5) Initial rapid exhumation must have followed granulite facies metamorphism in order to preserve the granoblastic textures and some of the peak metamorphic mineralogy. However, on the basis of age data, Keppie *et*

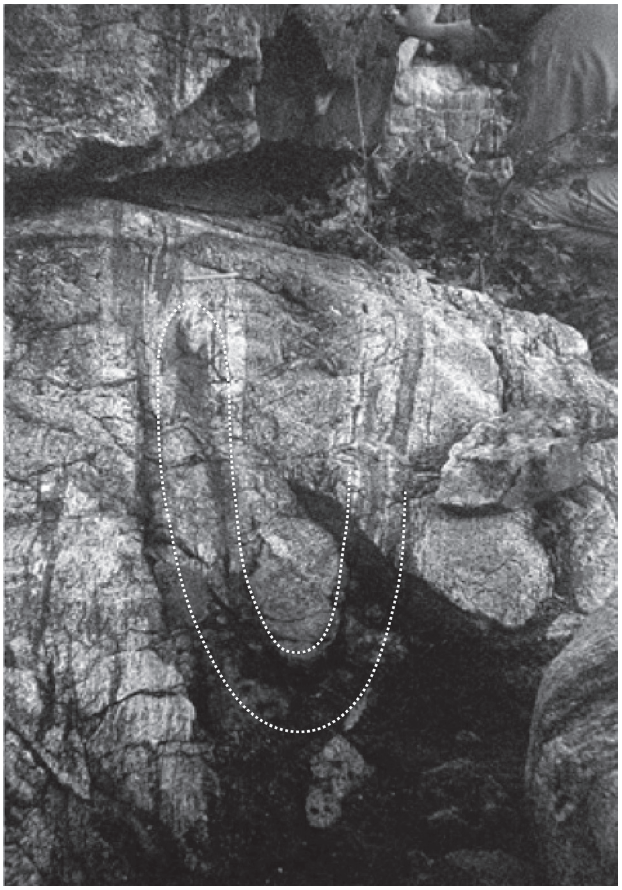

Figure 6. F_1 refolded about F_2 to produce a Type III (refolded isocline) interference pattern in the AMCG suite.

al. (2006) suggested that the Novillo Gneiss cooled from ~660°C at 928±2Ma to 325±25°C by 697±7 Ma, a relatively slow cooling rate of 1.45 °C/my.

(6) Following exhumation, a suite of porphyritic mafic dikes were intruded at *ca.* 546±5 Ma (Keppie *et al.*, 2006). Preserved igneous textures and chilled margins indicate that these dikes were emplaced into a relatively brittle, cold host rock. Extrapolation of the 1.45 °C/my cooling rate associated with its exhumation suggests that the Novillo Gneiss would have reached the surface (30 °C) by ~497Ma or 50 my after dike emplacement (Keppie *et al.*, 2006). The *ca.* 500 Ma exhumation coincides with deposition of the oldest latest Cambrian strata on the Oaxacan Complex (Landing *et al.*, 2007). This suggests that exhumation of the Novillo Gneiss was related to rifting in Oaxaquia.

(7) The final significant tectonothermal event in the Novillo Gneiss is associated with its tectonic juxtapositioning against the Granjeno Schist along the NNW-trending dextral shear zone that separates the two units. The event is manifest in brittle deformation and widespread greenschist facies retrogression of the Novillo Gneiss and the porphyritic mafic dikes. It is most likely to have accompanied development of the weak foliation in the leucogranite emplaced into the shear zone, which has yielded a $^{40}Ar/^{39}Ar$ age of 313±7 Ma on muscovite, recording cooling through ~350°C (Dowe *et al.*, 2005).

Comparison with the Oaxacan Complex

Broad similarities between the Mesoproterozoic (*ca.* 1 Ga) exposures in Mexico were instrumental in the proposition by Ortega-Gutiérrez *et al.* (1995) for the existence of the microcontinent "Oaxaquia" as the basement 'backbone of Mexico'. The largest of these exposures, the Oaxacan Complex (Figure 1), is generally regarded as the Oaxaquia architype (*e.g.*, Keppie, 2004). It is also the southernmost exposure and so is used here to test the continuity of the Mesoproterozic basement (and hence the integrity of Oaxaquia) by comparing its tectonothermal evolution (*e.g.*, Keppie *et al.*, 2001, 2003; Solari *et al.*, 2003) with that of the Novillo Gneiss, the northernmost exposure.

The Novillo Gneiss and Oaxacan Complex share many similarities (Keppie and Ortega-Gutiérrez, 2010; Weber *et al.*, 2010). Both comprise older suites of similar age (Novillo Gneiss: 1235–1115 Ma, Cameron *et al.*, 2004; Oaxacan Complex: ≥1350 – ≥1140 Ma, Solari *et al.*, 2003) and similar arc/back-arc geochemical signatures that Keppie and Ortega-Gutiérrez (2010) suggest reflect their location on the active northern margin (present day coordinates) of Amazonia (Figure 7). The Oaxacan Complex also records migmatization dated at 1106±6 Ma (U-Pb zircon; Solari *et al.*, 2003) that is designated the Olmecan event. Although the migmatite in the Novillo Gneiss has not been directly dated, it is of similar stromatic character and is interpreted to have accompanied emplacement of the older suite during the interval 1235–1115 Ma.

The older suites of both the Novillo Gneiss and Oaxacan Complex are also intruded by AMCG suites of similar age (Novillo Gneiss: 1035–1010 Ma, Cameron *et al.*, 2004; Oaxacan Complex: 1012–1006 Ma, Solari *et al.*, 2003, Weber *et al.*, 2010), and both underwent granulite facies metamorphism at similar times (Novillo Gneiss: 990±5 Ma, Cameron *et al.*, 2004; Oaxacan Complex: 1004-972 Ma, Solari *et al.*, 2003, Weber *et al.*, 2010), followed by exhumation and low-grade deformation. The high-grade metamorphism is attributed by Keppie and Ortega-Gutiérrez (2010) to either arc-continent (proto-Avalonia – Amazonia) or, following Li *et al.* (2008), continent-continent (Amazonia–Baltica) collision (Figure 7), a scenario favored by Weber *et al.* (2010).

In addition, both complexes are tectonically juxtaposed against similar Paleozoic sequences (the Granjeno Schist and Acatlán Complex, respectively) that comprise metasedimentary and metavolcanic rocks interpreted to be continental slope or accretionary prism deposits (Ortega-Gutiérrez *et al.*, 1999; Dowe *et al.*, 2005; Keppie *et al.*, 2006). The bounding faults in both cases are major dextral shear zones of late Paleozoic age (Elías-Herrera and Ortega-Gutiérrez, 2002; Dowe *et al.*, 2005). Finally, both

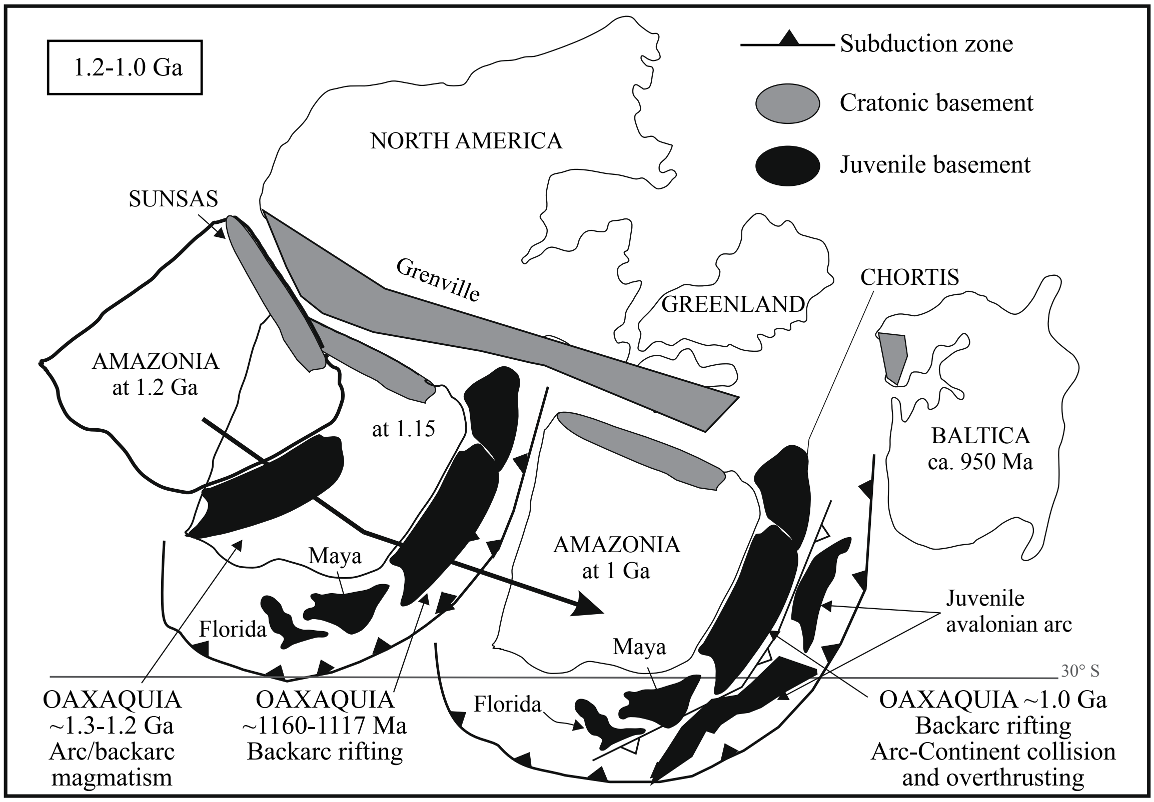

Figure 7. Reconstructions of Rodinia for the interval 1.2–1.0 Ga showing location of Oaxaquia on the leading edge of northern Amazonia during its sinistral drift relative to eastern Laurentia (simplified from Keppie and Ortega-Gutiérrez 2010).

the Novillo Gneiss and Oaxacan Complex are overlain by undeformed Lower Paleozoic strata of Gondwanan affinity (Stewart *et al.*, 1999; Landing *et al.*, 2007).

Strong similarities are also evident in the deformational histories of the Novillo Gneiss and Oaxacan Complex. Both complexes record a similar deformational sequence in which a high-grade, banding-parallel foliation that is axial planar to intrafolial folds is refolded by locally rootless isoclinal folds with variable symmetry and no axial planar fabric (assigned to the 1004–978 Ma Zapotecan Orogeny in the Oaxacan Complex: Solari *et al.*, 2003). Both complexes also contain ubiquitous, mineral lineation-parallel, mylonitic quartz ribbons. Given the complex Phanerozoic structural history of southern Mexico, it is not surprising that the present orientation of the structures in the two complexes is different: a steeply NE-dipping, composite foliation and variably plunging stretching lineations in the Novillo Gneiss, versus consistently NW-plunging stretching lineations and the metamorphic banding/composite foliation deformed about a NW-plunging upright fold in the Oaxacan Complex (Solari *et al.*, 2003). Furthermore, the sense of shear in the Novillo Gneiss is oblique, with sinistral and reverse (NE over SW) components, whereas it is SE-vergent thrusting in the northern Oaxacan Complex (Solari *et al.*, 2003). However, for the most part, the structures have the same *relative* orientations, such that the kinematic data for both complexes becomes concordant with a simple ~45° rotation about to pole to their coplanar metamorphic banding. This suggest that their present differences result from local late structural reorientation, although some may reflect decoupling of the middle-upper orogenic crust from a 5–10 km thick, hot (≥700°C), weak lower crust at a depth of ~30 km (Jamieson *et al.*, 1998).

In both the Novillo Geiss and Oaxacan Complex a period of static metamorphism is recorded at the same time (990±5 Ma and 1004–978 Ma, respectively) and was followed by exhumation. Peak metamorphism took place deeper in the Novillo Gneiss (8.9–9.7 kbar; Orozco, 1991) than in the Oaxacan Complex (7.2–8.2 kbar; Mora *et al.*, 1986), and the latter initially cooled much faster (~8 °C/my between 978 Ma and 945 Ma followed by ~2 °C/my: Keppie *et al.*, 2004) than the Novillo Gneiss (~1.45 °C/my) during exhumation.

Like the Novillo Gneiss, the Oaxacan Complex contains mafic dikes that predate granulite facies metamorphism. However, younger dikes equivalent to the porphyritic amphibolites in the Novillo Gneiss have not been reported. Hence, the Novillo Gneiss records an extensional event that is not observed in the Oaxacan Complex. The origin of the porphyritic amphibolite dikes is uncertain. However, Keppie *et al.* (2006, 2011) have suggested their emplacement could herald the separation of Avalonia from the northern margin of Amazonian, an event thought to be recorded in the Acatlán Complex with the onset of bimodal magmatism at *ca.* 500 Ma (Keppie et al., 2008). If so, the absence of these dikes in the Oaxacan Complex may simply reflect a more interior location relative to the developing continental margin.

CONCLUSIONS

The Mesoproterozoic Novillo Gneiss is made up of two granulite facies metamorphic igneous assemblages, an older suite dated at 1235-1115 Ma, which comprises ?migmatitic K-feldspar megacrystic metagranites and granite gneisses that intrude calc-silicates, and a younger AMCG suite comprising charnokitic gneiss and anorthositic-metagabbro emplaced at 1035–1010 Ma. Both suites are intruded by two sets of mafic dikes – a suite of garnet amphibolites that pre-date granulite facies metamorphism at *ca.* 990±5 Ma, and a suite of low-grade porphyritic amphibolites dated at *ca.* 546 Ma.

Both suites of gneisses were deformed by polyphase, penetrative fabrics (metamorphic banding, isoclinal folds, stretching and mineral lineations) at high grades of metamorphism culminating in top-to-the-NW sinistral thrusting. Subsequent granulite facies metamorphism produced ubiquitous granoblastic textures that overprint all earlier microfabrics and was followed by exhumation and the ensuing emplacement of the younger dikes. Dextral thrust juxtapositioning of the Novillo Gneiss against the adjacent Granjeno Schist, a polydeformed assemblage of Paleozoic metasedimentary, metavolcanic and serpentinized mafic-ultramafic rocks, took place in the late Paleozoic and was accompanied by low-grade metamorphism.

Correlation of the Novillo Gneiss with the Oaxacan Complex of southern Mexico, proposed on the basis of broad similarities in lithologies, age and cover rocks, has been used in previous studies to support the existence of the microcontinent Oaxaquia (Keppie and Ortega-Gutiérrez, 2010; Weber *et al.*, 2010 and references therein). Such a correlation is supported by this study, which shows the structural style, deformational sequence and tectonothermal history of the two complexes to be closely similar.

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