Arc rifting of the Carolina terrane in northwestern South Carolina

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ABSTRACT

Recent mapping and whole-rock geochemistry studies demonstrate that mafic metavolcanic rocks found along the boundary between the exotic Carolina terrane and the Inner Piedmont formed in a subduction-related volcanic arc and do not represent the Iapetan suture. Mafic metavolcanic rocks are spatially and genetically related to zoned mafic-ultramafic intrusive complexes. These rocks are similar to those found in other ancient and modern volcanic island arcs where ankaramites and picrites are well known, and they are locally associated with zoned complexes, e.g., Sierra Foothills–Klamath Mountains of the western U.S. Cordillera. We propose that prior to accretion to Laurentia in the early to middle Paleozoic, the Carolina arc terrane underwent an episode of intra-arc rifting which allowed primitive arc magmas to ascend and erupt without significant crystal fractionation or lithospheric assimilation. This interpretation may help resolve some stratigraphic problems in the eastern part of the Carolina terrane (Carolina slate belt).

INTRODUCTION

The Carolina terrane is a composite volcanic arc of late Precambrian to Cambrian age exposed in the Piedmont of Georgia, the Carolinas, and Virginia. The origin of the Carolina terrane has been the subject of considerable debate. Previous geochemical interpretations have yielded conflicting interpretations for accumulation of the arc, including a primitive intra-oceanic arc (Whitney et al., 1978) and arc development on an active continental margin (Rogers, 1982). The discovery of a Middle Cambrian Acado-Baltic fauna in central South Carolina suggests that the Carolina terrane is exotic to North America (Secor et al., 1983).

The Kings Mountain belt in western South Carolina is a greenschist to lower amphibolite facies metavolcanic terrane that forms the western margin of the Carolina terrane. It is bounded on the west by middle to upper amphibolite facies schists and gneisses of the Inner Piedmont, interpreted by some workers to represent the metamorphosed sediments of the ancient North American slope and rise (Hopson and Hatcher, 1988). Some workers have also suggested that mafic and ultramafic rocks along this boundary form part of an ophiolite suite (Mittwede et al., 1987). However, neither the pseudostratigraphy of an ophiolite nor a regionally extensive melange terrane has been demonstrated along this trace.

A fundamental problem in the southern Appalachian Piedmont remains the contrast in volume of mafic volcanism between the western and eastern Carolina terrane. Rocks in the western part of the terrane are dominated by amphibolite and metagabbro (McSween et al., 1984), whereas to the east, felsic pyroclastic rocks are much more common (Secor, 1987). Mafic and ultramafic plutonic rocks of the Kings Mountain belt intrude these volcanic rocks and are associated with ankaramitic dikes that feed mafic flows. These plutonic rocks are chemically and petrologically similar to zoned mafic-ultramafic complexes of the western Cordillera (e.g., Snoke et al., 1982).

FIELD RELATIONS AND PETROLOGY

Detailed mapping in the western part of the Carolina terrane in northwestern South Carolina shows that a dominantly mafic volcanic section is intruded by heterogeneously zoned, ultramafic-mafic plutonic complexes, and that the resulting package has been deformed and has undergone greenschist to lower amphibolite facies metamorphism (Fig. 1; Horkowitz, 1984; Willis, 1984; Mittwede, 1989; Dennis, 1988, 1989). Because the relative volume of plutonic rocks and regional metamorphic grade increase to the southeast, it is probable that a north-to-south traverse along the trace of the boundary goes deeper into the volcanic pile. Consequently, workers in North Carolina (Horton, 1981) have seen a stratigraphically higher section than workers in South Carolina, and greenschist facies rocks exposed along the terrane boundary in northwestern South Carolina are exposed in the amphibolite facies terrane well east of the boundary in North Carolina.

Volcanic Rocks

Mafic to intermediate volcanic rocks, which include actinolitic amphibolites, banded amphibolites, feldspar- and pyroxene-phyric amphibolites, amygdaloidal greenstones, and mafic lapilli tuffs, comprise most of the section. Actinolitic amphibolites are inferred to be mafic or intermediate metavolcanic rocks on the basis of fine-grained epidote-plagioclase-quartz-filled amygdules, pumiceous lapilli, and plagioclase phenocrysts 1–2 mm in size. Less well laminated, more massive actinolitic amphibolites are interpreted to represent massive basaltic or basaltic andesite flows. We have not recognized pillow structures in these rocks. Ankaramites are common both as dikes that crosscut mafic volcanic rocks and as volcanic breccias. These rocks originally contained abundant centimetre-sized pyroxene phenocrysts, up to 40% modally, but all primary minerals, including clinopyroxene, have been replaced or altered. Pyroxene phenocrysts are typically replaced by fibrous actinolite, which forms pseudomorphs of the original grain shape. The mafic volcanic rocks have a strong mesoscopic foliation, but the occurrence of fine-grained, polygonal felsic phases and relatively coarse, idioblastic amphiboles are interpreted to imply recrystallization under static conditions.

Felsic volcanic rocks are volumetrically much less important than the amphibolites (Fig. 1). Locally felsic and mafic rocks are intercalated on a 1 to 10 m scale, and the boundaries between these rock types are gradational, based on relative proportions of felsic and mafic material. It has not been possible to discern facing or stratigraphic relations between the felsic and mafic volcanic units.

The mafic volcanic section is cut by narrow corridors of quartz-sericite schist which may be traced several kilometres along strike. These 100-m-wide zones are spatially associated with hypabyssal metagabbros and are interpreted to represent zones of hydrothermal alteration contemporary with volcanism. Felsic pyroclastic rocks include sillimanite-sulfide-quartz schists, with abundant sillimanite prisms (up to several centimetres long) that may compose >80% of the sample. These schists are interpreted to represent extensive hydrothermal alteration of an intermediate volcanic protolith.

Plutonic Rocks

There are three zoned mafic-ultramafic intrusive complexes in the map area: the Wildcat Branch complex (Horkowitz, 1984), the Hammett Grove metaigneous suite (largely serpentinite and metagabbro, Mittwede et al., 1987), and the Mean Crossroads complex (Dennis, 1988, 1989; Fig. 1). The intrusive complexes are typically <10 km in diameter and are crudely zoned from mafic-rich cores to more felsic, dioritic rims. Coarse-grained (~1 cm), foliated diorites and quartz diorites form the outermost zone and make up 60%–70% of the complexes. Foliated gabbro and hornblende gabbro locally enclose ultramafic cores and may compose

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10%–15% of the complexes. Grain size within these gabbros is generally 1 to 2 cm. Mappable layering has not been discerned within the metagabbros, though Mittwede et al. (1987) have recognized possible layering or a flow foliation in metagabbros of the Hammett Grove complex. Pyroxene, hornblende, and plagioclase are recognized as cumulate minerals within the metagabbros. The complexes have cores of coarse-grained (1–3 cm) pyroxenite or hornblende pyroxenite bodies typically <2 km in diameter. These cores make up 15%–20% of the complexes by area. Whole-rock chemistry indicates that these rocks must have been clinopyroxenites (>20 wt% CaO).

Small, foliated granite and granodiorite plutons that intrude the volcanic section are spatially independent of the zoned complexes and appear to be chemically unrelated to them. Biotite porphyry textures are notable among some members of this group: planar aggregates of biotite are commonly several millimetres thick and 1 cm or more in diameter. Medium-grained, isotropic diorites intrude the zoned complexes and metavolcanic rocks. We recognize that some of these diorites are postmetamorphic by hornfels contacts.

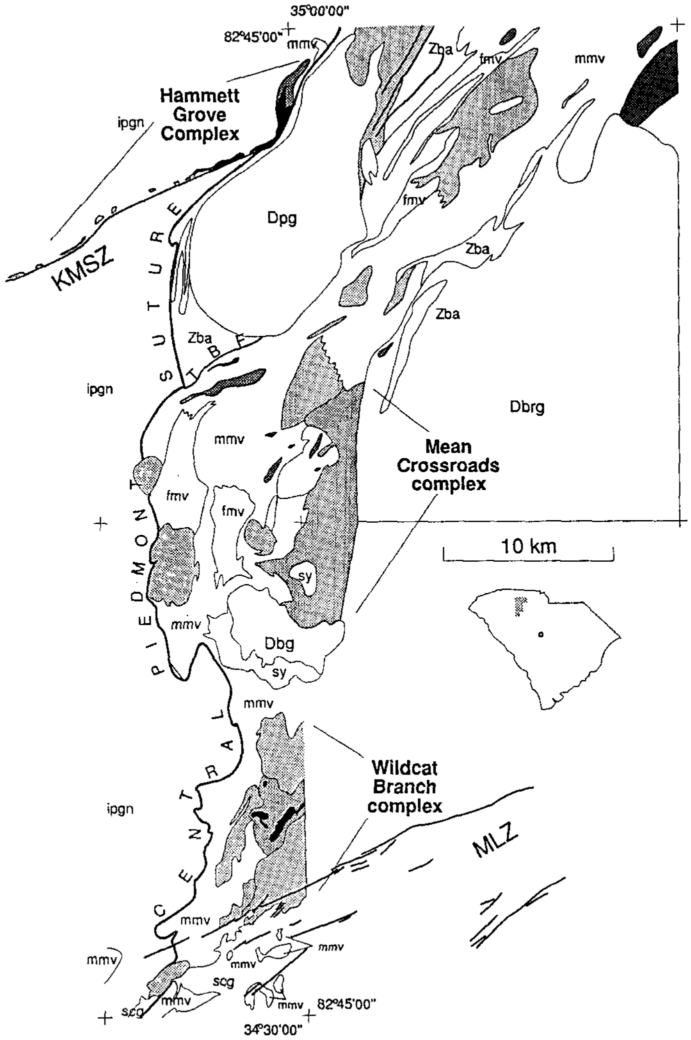


Figure 1. Simplified geologic map along terrane boundary in northwestern South Carolina, compiled from Dennis (1989), Horkowitz (1984), Mittwede (1989), and Willis (1984). KMSZ = Kings Mountain shear zone; MLZ = Middleton-Lowndesville zone; TBF = Tinsley Bridge fault; Dpg = Pacolet granite; Dbrg = Bald Rock granite; Dbg = Buffalo gabbro; sy = syenite; scg = Sand Creek granite; Zba = Battleground Formation; mmv = mafic metavolcanic; fmv = felsic metavolcanic. *Patterned plutonic complexes are foliated, premetamorphic intrusive* rocks: squares = metagranite; crosses = metadiorite; gray = metagabbro; black = ultramafite; ipgn = undifferentiated Piedmont terrane gneisses.

Structural Relations

Amphibolites compose the wall rock of the intrusive complexes and are also screens or xenoliths within complexes. No contact metamorphic effects have been recognized between the zoned complexes and the volcanic rocks they intrude. We interpret subsequent regional metamorphism to have overprinted any contact effects. Diorites and quartz diorites are locally mylonitic within the complexes. Mylonitic diorites commonly comprise 1–10-cm-thick hornblende-plagioclase-epidote layers alternating with epidote-plagioclase-quartz layers. Ductile fault rocks internal to the intrusive complexes and within the mafic metavolcanic terrane may be related to the intra-arc rifting proposed herein. A fault, informally referred to as the Tinsley Bridge fault, places amphibolites and mafic metavolcanic rocks against extensively altered felsic volcanic rocks. Timing and sense of movement on these faults are uncertain. They may be related to the Alleghanian shear zones described by Horton (1981), or they may be older faults.

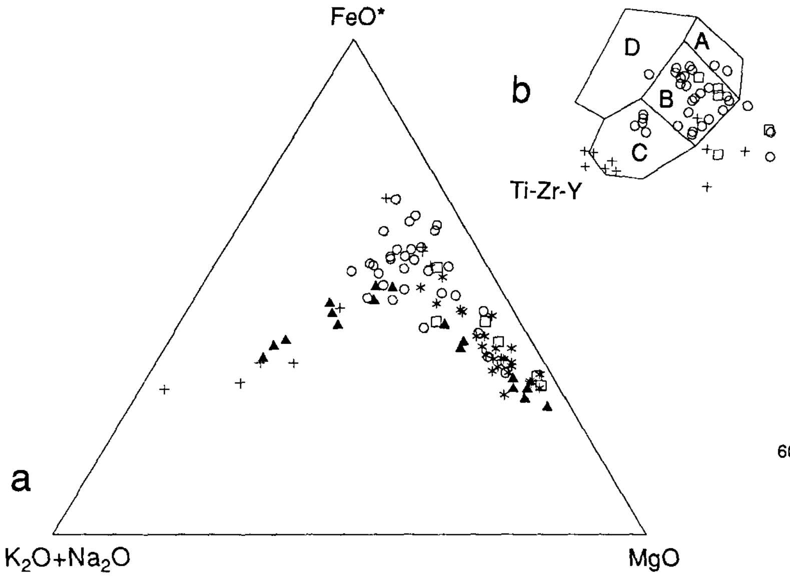
GEOCHEMISTRY

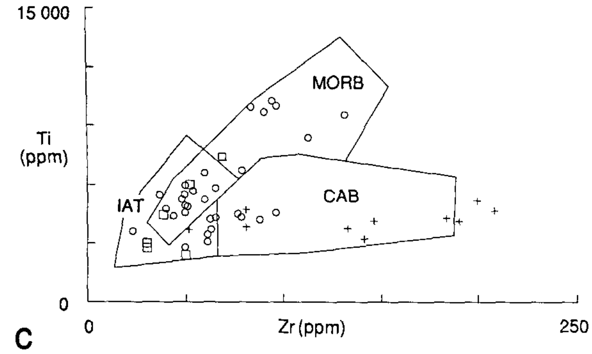
Approximately 50 samples of metavolcanic rocks (actinolitic amphibolites, banded amphibolites, meta-ankaramite dikes, and a few meta-rhyodacite tuffs) and 30 samples of metaplutonic rocks (diorites, gabbros, pyroxenites, and hornblende-pyroxenites) were analyzed for major and trace elements by X-ray fluorescence. The goal of our sampling was to obtain the freshest representative suite of the metamorphosed rocks in this area. We believe the resulting metavolcanic data set represents liquidus compositions of basalts and basaltic andesites for this part of the Piedmont. These data suggest that ratios of trace elements have remained constant over greenschist to amphibolite facies metamorphism.

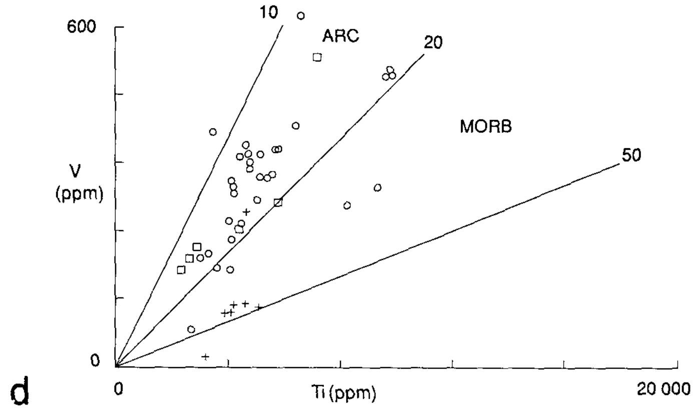
Metavolcanic and metaplutonic rocks of the western Carolina terrane show a fractionation trend on an AFM diagram that is intermediate between calc-alkalic and tholeiitic. This trend is nearly identical to that shown by volcanic rocks of the New Georgia Group of the Solomon Islands (Stanton and Bell, 1969), which include picrites, ankaramites, basalts, and feldspar-phyric basaltic andesites (Fig. 2A). Mafic metavolcanic rocks from this area have low TiO_2 contents, which do not increase with increasing fractionation. Low TiO_2 is characteristic of arc volcanic rocks and is in contrast to high Ti concentrations recognized in open-system MORB fractionation.

Trace element systematics of the mafic metavolcanic rocks support inferences drawn from the major element data. Most of the data plot in a field shared by calc-alkalic basalts, low-K arc tholeiites and ocean-floor basalts on a Ti-Zr-Y ternary diagram (Fig. 2B), ruling out an oceanic island basalt origin (field B). Mafic metavolcanic rocks plotted on a Ti-Zr diagram are generally in the low-K tholeiite and calc-alkalic basalt fields, yet several data overlap arc and mid-oceanic ridge basalt (MORB) fields (Fig. 2C).

Ti-V and Ti-Cr ratios yield less equivocal conclusions. A Ti-V plot shows a strong positive correlation between Ti and V, with Ti/V ratios between 10 and 20 (Fig. 2D). Only two high TiO_2 (>1.3%) samples lie in the MORB field; the others have very high V concentrations (≥400 ppm), thus indicating an arc origin. Arc volcanic rocks with >57% SiO_2 have low concentrations of both Ti and V, and higher Ti/V ratios (Shervais, 1982), reflecting hornblende or Ti-magnetite fractionation. A similar trend is seen in the low Cr-Ti ratios (Fig. 2E), most of the amphibolites being in a field defined by arc rocks (Pearce, 1975). Here only one high-TiO_2 sample falls in the MORB field (Fig. 2E). Other samples in the MORB field have low Ti and high Cr and may represent partial cumulates or picritic basalts. We interpret the mafic metavolcanic rocks that we have studied from the western part of the Carolina terrane to have formed in a subduction-related setting, on the basis of these data and the field relations outlined above. Those mafic metavolcanic rocks in our suite with high







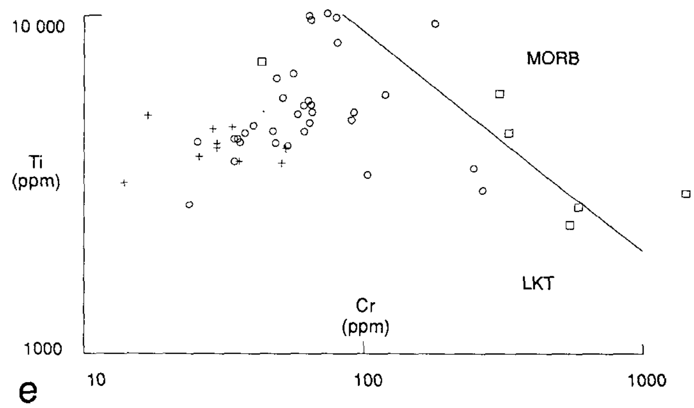


Figure 2. Major and trace element geochemistry for 50 mafic and ultramafic volcanic rocks from western Carolina arc terrane. In all diagrams, circles indicate metavolcanic rocks with $SiO_2 < 57$, squares indicate ankaramites, crosses indicate metavolcanic rocks with $SiO_2 > 57\%$, and asterisks represent metacumulates. A: AFM diagram comparing compositions of rocks of western Carolina arc terrane to those of New Georgia Group (triangles; Stanton and Bell, 1969). B: Ti-Zr-Y, after Pearce and Cann (1973). Ti-Zr-Y fields: A + B—low-K tholeiites; B + C—calc-alkalic basalts; B—ocean-floor basalts; D—ocean-island or continental basalts. C: Ti-Zr, after Pearce and Cann (1973). D: Ti-V, after Shervais (1982). See text for discussion. E: Ti-Cr, after Pearce (1975).

TiO_2 (>1.3%) may represent either remnants of an older oceanic crust substrate to the arc, back-arc-basin type lavas associated with intra-arc rifting, or highly evolved arc tholeiites.

DISCUSSION

Regional Significance of Zoned Complexes and Associated Volcanic Rocks

The association of felsic, intermediate, and mafic-ultramafic volcanic rocks with zoned peridotite-to-diorite plutonic complexes in ancient arc terranes has been mapped in the western Sierra foothills and Klamath Mountains in the western Cordillera (e.g., Pine Hill—Springer, 1980; Emigrant Gap—James, 1971; Bear Mountain—Snoke et al., 1981), north to the Canadian Cordillera (Duke Island—Irvine, 1974; Tulameen—Findlay, 1969), and in the mid-Cretaceous arc exposed on Tobago, West Indies (Frost and Snoke, 1989). The picritic and ankaramitic lavas commonly associated with these plutons (e.g., Logtown Ridge, Peñon Blanco—Saleeby, 1982; Rattlesnake Creek terrane—Wright and Fahan, 1988; Bridget Cove—Irvine, 1973; and Nicola Group—Mortimer, 1987) are inferred to represent the parent magmas of the ultramafic-mafic complexes. Snoke et al. (1982) compared their observations to those modern arc environments where ankaramites and picrites are well known and concluded that these relations in the Sierra-Klamath region record a period of intra-arc rifting. Recent studies of arc terranes in the western Pacific that are characterized by predominantly picrite-ankaramite volcanism (e.g., New Georgia Group, Solomon Islands—Ramsay et al., 1984; Vanuatu—Barsdell and Berry, 1990) have reached similar conclusions in modern arcs. Deep-seated faulting accommodates rifting and may provide conduits that allow highly mafic, primitive magmas to reach the surface without extensive fractionation. This rifting is commonly associated with the subduction of topographic highs on the downgoing plate (Ramsay et al., 1984; Barsdell and Berry, 1990). We interpret the observed outcrop distribution of mafic volcanic rocks and ultramafic to mafic plutonic rocks in northwestern South Carolina to record rifting of the Carolina arc prior to accretion to North America in the early to middle Paleozoic.

This interpretation may help resolve some stratigraphic problems in the eastern part of the Carolina arc terrane. For example, sequences of turbiditic wackes intercalated with thin amygdaloidal basalts unconformably overlie the Lincolnton metadacite in northeastern Georgia and southwestern South Carolina (Whitney et al., 1978; Secor, 1987). In the eastern Piedmont of South Carolina, felsic pyroclastic rocks of the Persimmon Fork Formation are unconformably overlain by turbiditic wackes, amygdaloidal greenstones, and mafic tuffs and flows of the Richtex formation (Secor, 1987). In North Carolina, felsic pyroclastic rocks of the Uwharrie formation are structurally overlain by a bimodal volcanic suite within the Albemarle Group (Seiders, 1978; Harris and Glover, 1988). Secor (1987) has presented the case for considering the contact between these felsic pyroclastic units and overlying turbidites and greenstones to be a pre-cleavage fault. An alternative solution is to consider this contact to be a depositional unconformity: the turbiditic wackes would represent arc-derived detritus shed into an intra-arc rift basin, and intercalated greenstones represent basaltic tuffs and flows deposited into this basin far from the axis of rifting in the western arc.

Tectonic Implications of the Model

The Inner Piedmont and eastern Blue Ridge define a tectonic element framed by ultramafic rocks. This element is bounded on the southeast by arc rocks of the Carolina terrane and the central Piedmont suture, and on the northwest by the western Blue Ridge and the Hayesville-Fries fault. This block has been interpreted to represent (1) a late Precambrian marginal basin developed on attenuated North American crust (Hopson and Hatcher, 1988), or (2) two or more highly disrupted terranes including a fore-arc/accretionary prism assemblage (Horton et al., 1989). The Carolina arc accumulated outboard of these terranes, either on thinned continental crust, or on older, amalgamated arc terranes. However, like other volcanic arcs developed on attenuated continental margins (e.g., Aleutians), the character of the basement on which the arc is assembled probably changes along strike.

It is possible that a tectonic melange may have formed in an accretionary prism between the Inner Piedmont and the Carolina arc terrane, or that oceanic crust may have been obducted at the time of arc accretion. However, there is no record of the existence of these rock types now. On the other hand, amphibolites superficially similar to those we have described occur elsewhere along the terrane boundary. At present, no conclusive evidence supports occurrence of former oceanic crust along the western margin of the Carolina arc terrane.

CONCLUSIONS

The western edge of the Carolina terrane in the northwestern South Carolina Piedmont comprises mafic and subordinate felsic volcanic rocks intruded by an ultramafic to mafic plutonic suite. Similarities in composition between these intrusive and extrusive rocks suggest that they are related. Detailed mapping shows that rocks of the volcano-plutonic complex share a common metamorphic and deformational history.

Regional geologic relations and major and trace element geochemistry unequivocally support an arc tectonic setting for the ultramafic-mafic, intrusive-extrusive suite. No evidence supports an obducted oceanic crust or melange model for mafic and ultramafic rocks along the terrane boundary in northwestern South Carolina. Consequently, the tectonic setting of the Carolina arc relative to more westerly terranes must be reexamined.

Geologic data from the western Carolina arc terrane indicate a comparison with the Mesozoic Klamath-Sierras arc and rifted arc terranes of the western Pacific. The association of ultramafic-mafic volcanic rocks intruded by rocks of roughly similar composition may represent a rifted arc terrane.

The rifted arc hypothesis may reconcile some stratigraphic problems in the eastern arc terrane—e.g., felsic metavolcanic rocks unconformably overlain by turbiditic wackes and thin basalts—as well as provide a working model for future detailed studies of the western Carolina terrane.

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