Separata de: Geological Society of America Bulletin. Colorado, USA. 89(4): 533-547, 1978.

Upper Mesozoic flysch of Tierra del Fuego and South Georgia Island: A sedimentologic approach to lithosphere plate restoration

R. D. WINN, JR.* *Department of Geology & Geophysics, University of Wisconsin, Madison, Wisconsin 94706*

ABSTRACT

The South Georgia Island segment of the North Scotia Ridge is interpreted as having once been adjacent to Tierra del Fuego, South America. The upper Mesozoic graywackes, mudstones, and tuffs of South Georgia (Cumberland Bay and Sandebugten strata) and Tierra del Fuego (Yahgan Formation and Tekenika Beds) are the infill of a marginal basin that formed between the South American continent and an active calc-alkalic arc. The former arc site is now occupied by the Patagonian batholith; ophiolites represent the former basin sea floor.

Sediment gravity flow fabrics, sedimentary structures, and bedding styles and relatively deep-water trace fossils (*Phycosiphon, Helminthopsis, Taenidium, Zoophycos, Chondrites, Scalarituba?, Lophoctenium?*) indicate deposition on submarine fans. Paleocurrent and petrographic analyses indicate bilateral infilling of the basin. The only known possible sources for the Sandebugten sandstones are silicic volcanic and interbedded sedimentary rocks of the Jurassic Tobifera Formation of South America; this evidence indicates former juxtapositioning of South Georgia and Tierra del Fuego. The Sandebugten-type sandstones and the Jurassic volcanic rocks have abundant quartz and plagioclase, uncommon potassic feldspar, and essentially no pyroxene and amphibole. Lithic fragments in these sandstones have identical counterparts in the Jurassic volcanic and sedimentary rocks. The Yahgan and Cumberland Bay clastic rocks were eroded chiefly from calc-alkalic volcanic rocks positioned south of their depositional areas. The latter sandstones are made up dominantly of andesite and dacite tuff and flow fragments. Plagioclase is common; quartz, ferromagnesian minerals, and mafic volcanic fragments are uncommon. Basin closure and deformation occurred during the Late Cretaceous Andean orogeny when the rocks were metamorphosed to prehnite-pumpellyite grade. South Georgia was translated relatively eastward, probably as the result of collision of the Drake Passage spreading zone with the continent during Oligocene to Miocene time.

INTRODUCTION

South Georgia Island, on the northern limb of the Scotia arc, is located about 2,000 km east of the southern tip of the South American continent (Tierra del Fuego; Fig. 1). The island is geologically anomalous in its present position. It is underlain by a thick, strongly deformed, flyschlike sequence that is intruded by silicic to intermediate plutonic rocks yet is surrounded by oceanic crust (Trendall, 1953, 1959; Ewing and others, 1971).

The flyschlike rocks of South Georgia have been divided into two units — the Cumberland Bay "type" or "series" and the Sandebugten "type" or "series"[1] (Trendall, 1953, 1959). The Mesozoic Cumberland Bay unit has been thought to be correlative with the Mesozoic flyschlike Yahgan Formation of Tierra del Fuego (Wilckens, 1933; Mathews, 1959; Katz and Watters, 1966; Dalziel and Elliot, 1973), suggesting that South Georgia once lay adjacent to Tierra del Fuego and south of Burdwood Bank (Fig. 2; Dalziel and Elliot, 1971, 1973). On the basis of structure and petrography the Sandebugten is thought also to be Mesozoic in age (see Dalziel and others, 1975). Until the study described here, no one had first-hand knowledge of both the South Georgia Island and Tierra del Fuego Mesozoic flysch. In this paper the Dalziel-Elliot reconstruction is investigated by testing correlation of the Mesozoic flyschlike units and determining their genesis.

This study compares the ages, depositional environments and dispersal patterns, deformation styles and metamorphic grades, and especially the provenance characteristics of the Mesozoic units as determined petrographically. The problem differs slightly from the correlation of units within continental interiors or on continental trailing edges. Flyschlike units typically are thick, poorly dated, likely to be strongly deformed, and lacking in marker horizons. Convergent–plate-margin sedimentary rocks such as the flyschlike units of South Georgia and Tierra del Fuego, reflect an active tectonic environment and thus are characteristically immature. Therefore, abundant source-area information partially offsets other problems in correlation. This study demonstrates that field-oriented sedimentologic studies can be used to decipher complex lithosphere plate motions. Moreover, pre-Jurassic plate movements can be determined only by sedimentologic and other field-oriented investigations. Preliminary sedimentologic and petrographic results from this study were reported by Dalziel and others (1975), Dott (1974), and Winn and Dott (1975, 1976, 1977).

Field work was conducted on South Georgia in January and February, 1973. Work was concentrated in the Cumberland Bay and Stromness Bay areas (Fig. 3), because both the Sandebugten and Cumberland Bay units are well exposed here and because movement across the island is nearly impossible. Movement in Cumber-

* Present address: Denver Research Center, Marathon Oil Company, P.O. Box 269, Littleton, Colorado 80160.

[1] As used by British geologists, the term "series" has no time-stratigraphic significance; this is the only way "series" is used in this paper.

Geological Society of America Bulletin, v. 89, p. 533–547, 12 figs., 1 table, April 1978, Doc. no. 80406.

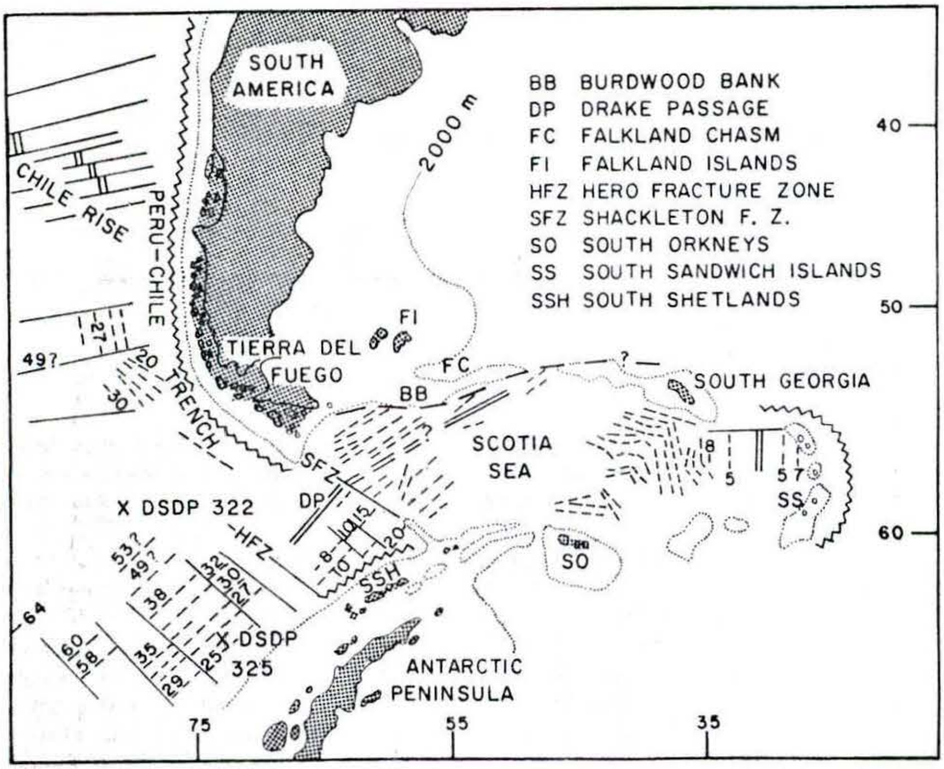

Figure 1. Tectonic configuration of Scotia Sea region (modified from Barker, 1970, 1972a, 1972b; Herron and Tucholke, 1976). Positioning of Drake Passage–West Scotia Sea spreading ridge is only approximate. Dated sea-floor magnetic anomalies are in million years. Recent DSDP holes in southeast Pacific are indicated (from Craddock and Hollister, 1976).

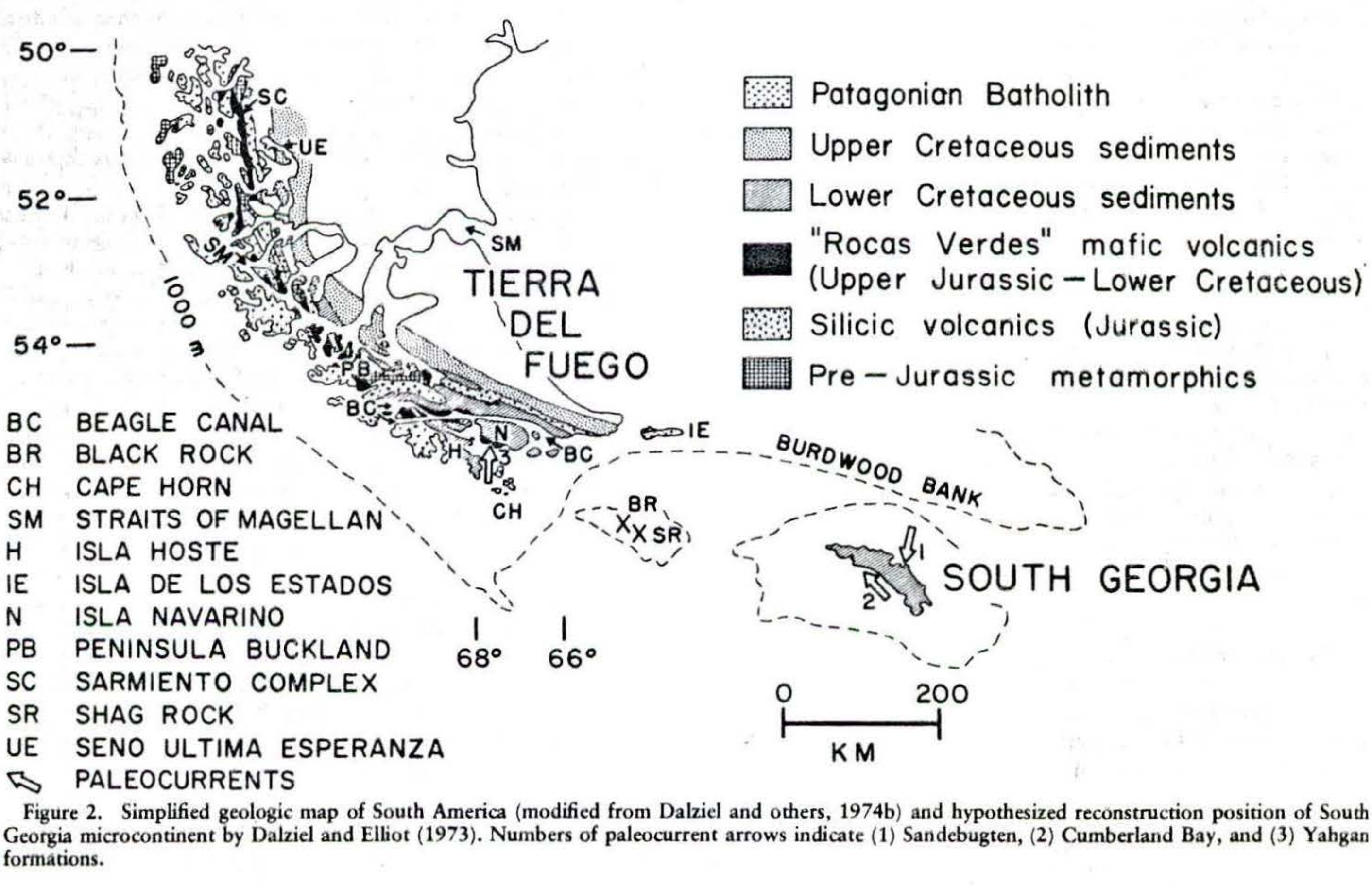

Figure 2. Simplified geologic map of South America (modified from Dalziel and others, 1974b) and hypothesized reconstruction position of South Georgia microcontinent by Dalziel and Elliot (1973). Numbers of paleocurrent arrows indicate (1) Sandebugten, (2) Cumberland Bay, and (3) Yahgan formations.

land Bay was accomplished by motorized rubber boats, but these were deemed unsafe for unsupported movement in the open ocean. Landings were made from the RRS *Bransfield* in the Bay of Isles and at Bird Island. Field work in Tierra del Fuego was conducted during March and April, 1973, in the area around Ushuaia, Argentina (Fig. 4), and during May and June, 1974 (with logistic support from the R/V *Hero*) on Isla Navarino, on Isla Hoste, along the western Beagle Channel, and in the Islas Wollastons and on Cape Horn (Figs. 2, 4).

TECTONIC AND STRATIGRAPHIC SETTING

Tierra del Fuego

Northeast of the southern Andean cordillera, southern South America consists mostly of Paleozoic and older rocks, deformed during the Permian-Triassic Gondwanan orogeny, overlain by extensive silicic volcanic and associated sedimentary rocks of Jurassic age (Tobifera Formation and equivalents) (Dutoit, 1937; Dalziel, 1974; Natland and others, 1974). Surface outcrop, drill-hole, and seismic-refraction data indicate that these volcanic rocks extend over almost the entire southern 1,500 km of South America and likely are present in the shelf basins off the eastern coast and on Burdwood Bank (Ludwig and others, 1968). A Middle to Late Jurassic age is provided by paleontologic and radiometric dating (Feruglio, 1949; Stepanicic, 1967; Natland and others, 1974).

The Tobifera volcanic rocks consist of fragmental and crystal tuffs, agglomerates, lavas, and ignimbrites. With few exceptions they are quartz latites to soda rhyolites in composition (Stepanicic and Reig, 1955; Dalziel and others, 1974a). Trace-element chemistry suggests that most of the volcanic rocks were derived from melted continental crust (R. Bruhn, 1977, oral commun.) and are related to the early stages of subduction beneath the western edge of South America, with perhaps a component due to volcanism associated with the break-up of Gondwanaland.

Jurassic volcanic rocks also exist farther north in South America, on the Antarctic Peninsula, and in Africa. Probable Jurassic-age volcanic rocks form much of the Antarctic Peninsula (see Adie, 1972; Dalziel and Elliot, 1973; Suárez, 1976). These range in composition from basalt to rhyolite, but most appear to be rhyolitic to andesitic. Even though small volumes of intermediate-composition volcanic rocks are present within the Tobifera Formation, the Jurassic volcanic rocks in the southern part of South America are exceptionally siliceous.

A discontinuous belt of Late Jurassic ophiolitic rocks along the western edge of southern South America, long called "Rocas Verdes," is interpreted as representing the floor of a small marginal ocean basin (Fig. 2; Katz, 1964, 1972; Dalziel and others, 1974b). Where best exposed, the Rocas Verdes consist of a layered gabbro zone at sea level that is cut by and passes upward into a sheeted dike complex, which is in turn overlain by basaltic pillows, breccias, and aquagene tuffs. Ultramafic components are not visible apparently only because of the level of exposure. The greenstones intrude and separate blocks and horsts of cratonic basement.

Overlying the ophiolites is an uppermost Jurassic to Lower Cretaceous flyschlike sequence (Yahgan Formation, Tekenika Beds; Fig. 5), which is a minimum of 5 to 6 km thick. The section is not well dated. The Tekenika Beds concordantly overlie the Yahgan, and paleontologic evidence suggests a late Mesozoic age for both units (Hoffstetter, 1957; Dott and others, 1977). Katz and Waters (1966) found the Yahgan Formation on Isla Navarino to consist of more than 3,000 m of graywacke, argillite, chert, and conglomer-

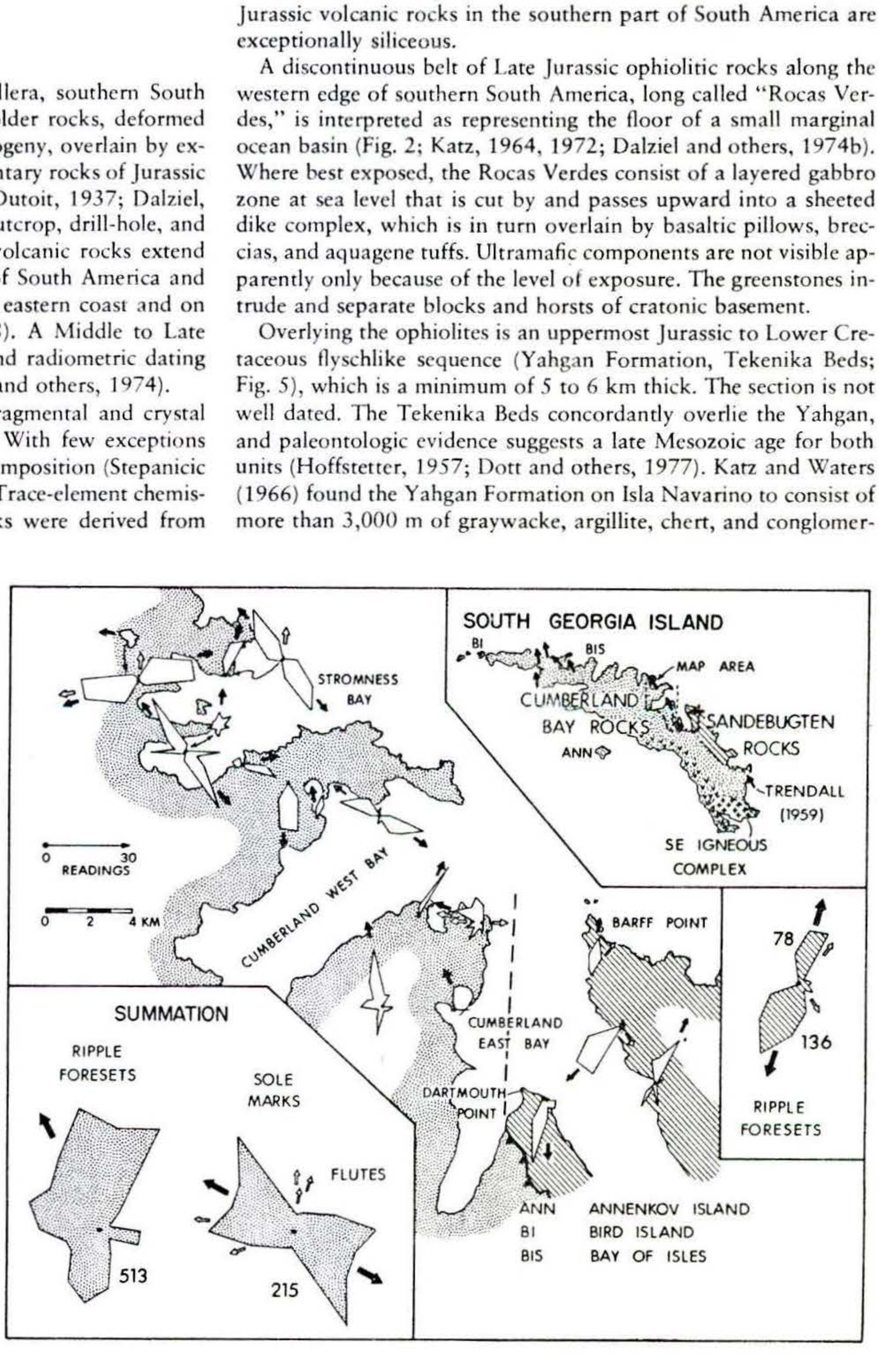

Figure 3. Geologic and paleocurrent map of South Georgia Island. Bimodal histograms indicate grooves; others depict cross-laminations. Open arrows in summation indicate single flutes; open arrows on map indicate single flutes or grooves. Stations in which both grooves and ripple foresets were measured are indicated (Stromness Bay area). Trendall's (1959) current directions are shown in inset. Dott (1974) discussed rotation procedures used in study of highly deformed South Georgia strata.

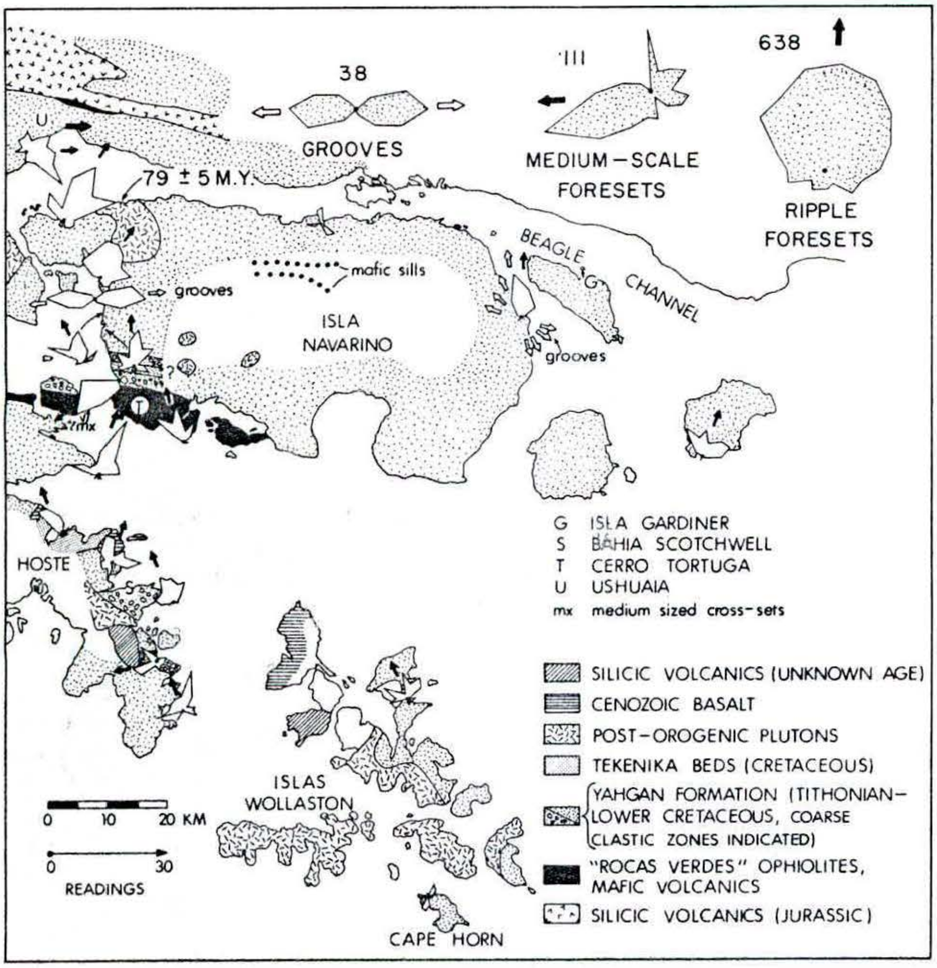

Figure 4. Geologic and paleocurrent map of Tierra del Fuego. Bipolar histograms indicate grooves; others represent medium-scale cross-sets or cross-laminations. Date of pluton intruding Yahgan rocks is given. Site near Ushuaia was too deformed to give anything but qualitative, easterly flow direction.

ate. The flysch in the Islas Wollaston is lithologically indistinguishable from the Yahgan Formation, but no paleontologic evidence is known there that would prove a similar age. The Mesozoic rocks along the western edge of southern south America were deformed during the mid-Cretaceous to early Cenozoic Andean orogeny by closure of the marginal basin (Dalziel and others, 1974b; Bruhn and Dalziel, 1977).

On the Pacific side of the greenstone-flysch belt are the intermediate-composition plutons of the Patagonian batholith (Fig. 2), which range in age from Middle Jurassic to Miocene but are mostly Cretaceous (Halpern, 1973; De Wit, 1977). The batholiths are thought to represent the roots of a former calc-alkalic arc that formed after rupture of the continent's edge during formation of the marginal basin (Dalziel and others, 1974b, 1975). The Antarctic Peninsula was probably a continuation of the late Mesozoic arc (Dalziel, 1974; Suárez, 1976).

South Georgia Island

The island is underlain mostly by a sequence of graded graywacke and mudstone flysch at least 5,000 m thick. Trendall (1953) divided the rocks into the Cumberland Bay and Sandebugten units (Fig. 3) on the basis of structural and lithologic differences. The Cumberland Bay is rich in andesitic debris and has interbedded volcanic flows; the Sandebugten is quartzose and lacks flows. In the areas observed by Trendall, the units have opposed vergences, the Cumberland Bay being overturned to the northeast, the Sandebugten to the southwest. Dalziel and Bruhn (in Dalziel and others, 1975) confirmed the contemporaneous deformation between the units as postulated by Trendall (1959). The units are separated by a clear thrust contact (see Fig. 5 in Dalziel and others, 1975). Dating of both units is poor, but an Early Cretaceous age is indicated by fossils in the upper part of the Cumberland Bay. The Sandebugten has yet to be dated paleontologically, but the lack of an older deformation fabric seems to demand that it was deposited after the widespread Permian-Triassic Gondwanan orogeny.

The southeast end of the island is underlain by a complex igneous, plutonic, and contact metamorphic terrane (Trendall, 1959). Intrusive rocks include granite, gneiss, migmatite, quartz diorite, and gabbro bodies. In this area pillow lavas are interbedded with Cumberland Bay sedimentary rocks. The gabbros and pillow lavas might be genetically related to the ophiolite sequences in southern South America (see Suárez and Pettigrew, 1976).

Tectonic Setting of Scotia Sea

Where sufficient seismic and petrologic data have been obtained, the various ridge segments of the Scotia arc have been shown to have continental crust (see Griffiths and Barker, 1972; Dalziel and Elliot, 1973). The only exception is the very young (4 to 8 m.y. old), dominantly tholeiitic South Sandwich volcanic chain formed on oceanic crust (Fig. 1; Baker, 1968; Ewing and others, 1971). Burdwood Bank appears seismically continental, although it is separated from the Falkland Plateau to the north by a strip of

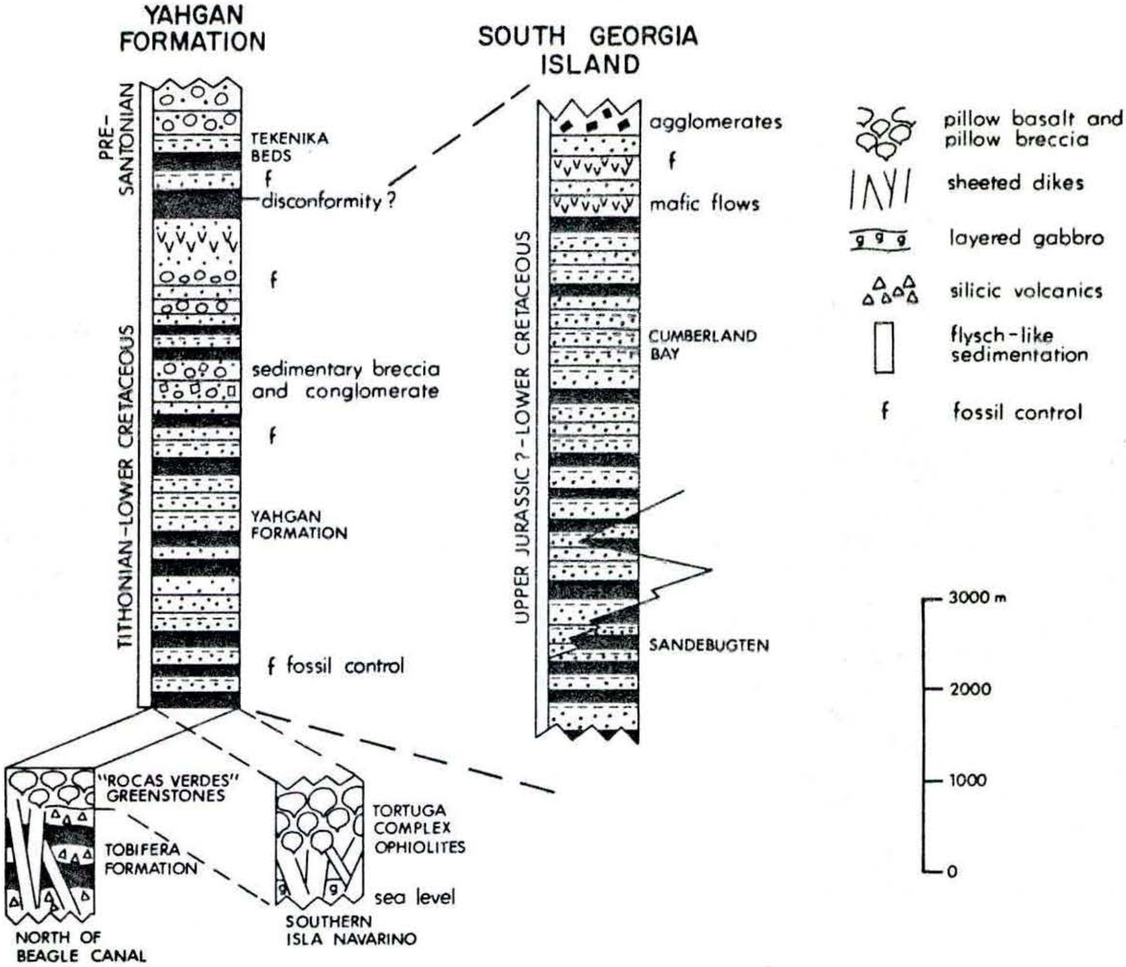

Figure 5. Correlation chart of Mesozoic rocks of southern Tierra del Fuego (Katz and Watters, 1966; this study) and South Georgia (this study). Note two different pre-Yahgan sequences — silicic volcanic rocks on cratonic margin (north) and ophiolites of marginal basin (south). Yahgan Formation may be only 4 to 5 km thick.

oceanic crust (Ludwig and others, 1968). The South Georgia platform data are ambiguous — the recorded seismic-refraction velocities might correspond to a continental-type basement dipping to the east, or to a quasi-oceanic layer (oceanic layer 3) dipping north (Ewing and others, 1971, p. 7127).

Seismic-refraction and bathymetric investigations have shown the Scotia Sea to have an oceanic crust, although the crustal structure is complex (see Barker, 1972a, 1972b; Ewing and others, 1971; Griffiths and Barker, 1972). Two active spreading centers, the Chile Rise and a ridge in the East Scotia Sea, and one inactive spreading zone in the Drake Passage are present (Fig. 1). A seismically active trench with intermediate- and deep-focus epicenters lies east of the South Sandwich chain (Heezen and Johnson, 1965). The seismically inactive southern segment of the Peru-Chile Trench extends south along the west coast of South America from lat 46 °S until truncated in the vicinity of the Drake Passage spreading zone (Hayes, 1965). An inactive trench is present parallel to and northwest of the South Shetland Islands (Barker, 1972a, 1972b).

AGE, SEDIMENTOLOGY, AND GENESIS OF YAHGAN AND CUMBERLAND BAY STRATA

Age

An assemblage of fossils collected from the upper part of the Cumberland Bay strata on Annenkov Island (see Fig. 3) were identified by Wilckens (1937, 1947) as being Early Cretaceous (late Aptian) in age. Identifiable ammonites included *Puzosia, Tropaeum,* and *Sanmartinoceras,* and a new form, *Georgioceras.* Casey (1961, p. 56) thought that the *Puzosia* more closely resembled the slightly older *Pleisiopiticeras* (Early Cretaceous, Hauterivian) and that the *Georgioceras* more closely resembled Neocomian than Aptian ammonites. Belemnite fossils from Annenkov were dated as late Aptian(?)–Albian by Pettigrew and Willey (1975). Belemnites in Cumberland Bay–like morainal debris were dated by Stone and Willey (1973) as Late Jurassic–Early Cretaceous.

Hoffstetter (1957) summarized and updated paleontological evidence from the Yahgan Formation and, mostly on the basis of belemnite and *Inoceramus* remains, concluded that the unit is Cretaceous and possibly Upper Jurassic (Tithonian). A fossil of Early Cretaceous age (Neocomian; *Favrella americana* or F. *steinmanni)* was found on Gardner Island (Fig. 4; Halpern and Rex, 1972). M. Thompson of the British Antarctic Survey and R. H. Dott, Jr. identified ammonites found during the present study on Isla Hoste at Bahia Scotchwell and the bay just to the south (Fig. 4) as also probably being a species of *Favrella.* The mudstones immediately overlying the Tobifera Formation on Isla de los Estados (Fig. 2), here interpreted as equivalent in age to the base of the Yaghan Formation, have been dated from *Belemnopsis* remains as Late Jurassic (Tithonian; Harrington, 1943). The Yahgan Formation, and thus the concordant Tekenika Beds, are certainly older than the isotopically dated 79 ± 5–m.y.-old (approximately Santonian or Campanian, Late Cretaceous) crosscutting pluton on Isla Navarino and Isla Hoste (Fig. 4; Halpern and Rex, 1972). Although the data are skimpy, both appear to have been deposited chiefly during Early Cretaceous time, but there is evidence that the Yahgan deposition may have begun in latest Jurassic time.

Lithologies, Bedding Styles, and Sedimentary Structures of Yahgan and Cumberland Bay Units

The Yahgan and Cumberland Bay units consist dominantly of interbedded graywackes and mudstones; both contain diamictites, conglomerates, and sedimentary breccias. Both units have sedimentary structures expected for deposition by sediment gravity flow (see Middleton and Hampton, 1973). Grading is very common in the sandstones, as are sole markings, flames and load structures, rip-up mudstone intraclasts, and convolute bedding. Sandstones are all poorly sorted, and most can be described using Bouma-interval terminology. Penecontemporaneous slumps are uncommon, but small ones are present in both units.

Conspicuous white quartz-prehnite strata, common in the Yahgan Formation and Cumberland Bay, range in thickness from a few millimetres to as much as 20 cm. Strata consisting almost entirely of prehnite and quartz most commonly appear massive. The "purity," thinness, and persistence of these quartz-prehnite beds, and the presence, although uncommon, of shard and ash fabrics indicate that these units represent former tuffs and tuffaceous sediments. Much of this tuffaceous sediment was reworked by sediment gravity flows or bottom currents.

The sequences in both regions coarsen upward (see Fig. 5). Agglomerates are present only in the upper part of the Cumberland Bay in the southwestern part of South Georgia and on Annenkov Island; on the latter they are interbedded with volcanic flows (Trendall, 1959; Suárez and Pettigrew, 1976). The basal part of the Yahgan Formation in the Beagle Channel area is fine grained and thinly bedded or laminated. Coarser strata are present in the upper part of the Yahgan Formation on Isla Navarino and in southern Isla Hoste and in the Islas Wollaston flysch. The coarsest beds, with boulders as large as 2.5 m, occur in southwestern Isla Navarino. Although much coarser than the average and containing medium-scale cross-bedding, these beds were also deposited from sediment gravity flows (Winn and Dott, 1976, 1977).

Trace Fossils

The trace fossils found in both units were clearly made by more or less systematic deposit feeders. *Phycosiphon, Scalarituba?, Lophoctenium?, Helminthopsis, Chondrites, Taenidium, Gyrochorte,* and *Paleophycus* are present in the Cumberland Bay (also see Wilckens, 1947); *Chondrites, Phycosiphon, Zoophycos,* and *Helminthopsis* ichnogenera were identified from the Yahgan Formation. The assemblage generally corresponds to the *Chondrites* facies of Chamberlain (1971), which he believed typical of bathyal depths. No characteristically shallow-water forms were found.

Deep-Sea Fan Deposition for Yahgan and Cumberland Bay Strata

The greatest volume of modern turbidite sequences is found on submarine fans or cones built at the bases of the continental slopes (see Nelson and Kulm, 1973; Normark, 1974). The area and volume of modern deep-sea fans supports the analogy for ancient deposits (Mutti, 1974) and specifically for the Yahgan and Cumberland Bay strata. Both units have deep-water trace fossils compatible with the ocean depths in which contemporary fans are being deposited.

Paleocurrents

The paleoccurent analyses are based mostly on measurements of ripple cross-laminations and grooves. Additional directional evidence was obtained from a few flutes (in both units), and in the Yaghan Formation from medium-scale cross-stratification, rarely observed imbrication, and a rippled surface. The results (Figs. 3, 4), indicate that both the Yahgan and Cumberland Bay strata were deposited by currents flowing generally north or northwest.[2]

The cross-lamination measurements in this study are replicable, are not highly dispersed, and generally agree with groove measurements in the same localities. On South Georgia, the Cumberland Bay groove marks have a bipolar northwest-southeast trend, but these are resolved to a northwest direction by considering associated cross-laminations and the few flutes (Fig. 3). The results agree closely with Trendall's (1959) more qualitative evaluation of current directions as deduced from ripple foresets at several scattered localities (Fig. 3, inset).

Petrography

Constitutents. In addition to specimens I collected, several samples from Annenkov Island (Fig. 3) were supplied by geologists of the British Antarctic Survey. None of the major constituents in the sandstones (Table 1) are unique to either the Cumberland Bay of South Georgia or the Yaghan Formation of Tierra del Fuego (see footnote 2 to order copy of Appendix Table 2, Detrital Constituents of Yaghan Formation and Cumberland Bay Sandstones). The rocks contain trace amounts of epidote, biotite, opaques, muscovite, apatite, zircon, tourmaline, sphene, and plant and shell debris.

Modal Analysis. Point counts were made of detrital constituents (Table 1); pseudomorphed and altered grains were identified as to their original compositions wherever possible. The sandstones are all very poorly sorted (matrix constitutes 13% to 40% of the average sandstone); therefore, all detritus slightly thicker than the slide was identified as grains, and only material finer than about 0.03 mm was counted as matrix (see Dott, 1964). One effect of the deformation and alteration common in sandstones from both South Georgia and Tierra del Fuego is to obscure the distinction between lithic grains and matrix. During point counting, areas were identified as lithic grains only if grain outlines were discernible. Because a range from unaffected to moderately affected samples was used from both units, I do not feel that this procedure hinders the petrographic comparison.

Two compositional modes, intermediate volcaniclastic and quartz rich, are present in the Yahgan Formation and Cumberland Bay sandstones (modes are subdivided in Table 1 and Fig. 6). The lithic clasts in almost all sandstones are dominantly volcanic rock

---

[2] See Appendix Table 1, Summary Statistics for Orientations of Current Structures. Copies of this and the other Appendix tables may be obtained by ordering GSA supplementary material 78-3 from Documents Secretary, Geological Society of America, 3300 Penrose Place, Boulder, Colorado 80301.

TABLE 1. SUMMARY OF DETRITAL MODES OF YAHGAN, CUMBERLAND BAY, AND SANDEBUGTEN SANDSTONES

	Yahgan Formation			Cumberland Bay			Intermediate volcaniclastic rocks	Sandebugten	
	Intermediate volcaniclastic rocks		Quartzose[*] sandstones	Intermediate volcaniclastic rocks		Quartzose[*] sandstones		Quartzose sandstones	
	Avg	Range		Avg	Range			Avg	Range
Lithic fragments	69.7 (6.2)[‡]	24–95	21.9	81.1 (±5.2)	54–95	43.1	79.2	43.1 (±6.6)	17–59
Plagioclase	22.9 (±5.4)	1–75	17.3	15.1 (±4.7)	4–37	26.1	17.2	19.4 (±5.2)	8–39
Potassic feldspar	0.1	0–1	1.2	0.1	0–1	1.1	tr.	1.8	0–1
Quartz	3.6 (±3.1)	0–14	58.9	2.4 (±1.4)	0–10	28.4	3.5	35.4 (±6.3)	23–59
Pyroxene	1.1	0–16	0	0.3	0–3	0	tr.	tr.	0–tr.
Amphibole	1.1	0–29	tr.	tr.	0–1	0	tr.	tr.	0–1
Biotite	tr.	0–tr.	tr.	tr.	0–tr.	0.2	0	tr.	0–tr.
Muscovite	tr.	0–tr.	tr.	tr.	0–tr.	0.1	0	tr.	0–1
Epidote	0.1	0–1	0.1	0.1	0–1	0.2	tr.	0.1	0–2
Opaques[†]	0.6	0–3	0.6	0.8	0–2	0.9	0.1	0.2	0–3
Plant and shell debris	tr.	0–3	tr.	tr.	0–1	0	0	tr.	0–1
Polycrystalline quartz/total quartz	0.18			0.15				0.50	
Plagioclase/total feldspar	0.99			0.99				0.92	
Volcanic rock fragments/total unstable lithic grains	0.99			0.99				0.97	
Mica (%)	<1			<1				<1	
No. of specimens	55	..	8	37	..	3	3	19	..

Note: At least 300 counts were made per sample; matrix counts were excluded to compute clast percentages. Points falling on recognizable crystals in lithic grains were counted as part of the lithic grain category. Polycrystalline quartz and chalcedony grains are included in the Q category only if they contain miniscule amounts of mica or opaques; otherwise they are included with the labile lithic fragments. All values in percent.

[*] Most samples in these categories are highly deformed and altered; as a consequence, not all point counts are replicable.

[†] All opaques are included herein; it is almost impossible to determine modes from metamorphic forms where both are present in the same sample.

[‡] The range is determined from the average counts at a 95% confidence interval (from Van de Plas and Tobi, 1965).

fragments. Plagioclase is moderately abundant, quartz much less so. Quartz is very abundant, though, in a few samples wherein it is associated with siliceous volcanic fragments.

Rock fragments. Many of the rock fragments are severely altered, but even within most of these grains, relict textures and structures are strongly indicative of the original rock type and composition (results summarized in Fig. 7; see footnote 2 to order copy of Appendix Table 3, Lithic Fragment Classification, and Appendix Table 4, Comparison of Lithic Fragment Abundances of Yaghan, Cumberland Bay, and Sandebugten Sandstones). Most siliceous volcanics are vitrophyric or hyalopilitic; andesitic flows tend to be porphyritic with a pilotaxitic groundmass; intergranular texture is almost exclusively confined to basalt. Feldspar microlites, amygdules, and relict shard or ash textures indicate that almost all of the microcrystalline to cryptocrystalline, turbid, green to gray or brown phyllosilicate grains common in most Cumberland Bay and Yahgan sandstones were derived originally from glassy rocks of an intermediate composition. The felsite grains were derived chiefly from dacitic and rhyolitic flows and tuffs, but a few appear to result from the albitization of intermediate volcanic fragments. Nonvolcanic rock clasts include quartzose sedimentary grains and uncommon shell fragments.

Source Terranes. The Yahgan Formation and Cumberland Bay units cover identical areas of the QFL diagram and have identical lithic fragment types (Figs. 6, 7). The two compositional modes recognized are the following.

Intermediate-volcaniclastic Mode. More than 95 percent of the Yahgan and Cumberland Bay sandstones fall in this category. These sandstones consist dominantly of volcanic lithic fragments with lesser amounts of plagioclase and small quantities of quartz. This mode has petrographic characteristics indicating derivation from a moderately siliceous but still intermediate-composition (calc-alkalic) volcanic terrane (compare Table 1 here with Dickinson, 1969). Rock-fragment types and abundances between the sandstones of the two units are almost identical; most are andesite and dacite flow and tuff fragments (compare Table 1, Figs. 8 and 9, and histograms of Fig. 6). The almost identical petrographic characteristics indicate very similar calc-alkalic volcanic provenances for both units. Paleocurrent data position these sources approximately to the south of their respective depositional areas. The Yahgan and Cumberland Bay source terranes are slightly atypical for most calc-alkalic volcanic rocks, in that they are fairly siliceous both in detrital mode abundances (ferromagnesian minerals are less abundant than quartz) and lithic fragment types (compare Fig. 7 and Table 1 to Dickinson, 1974). Within both units, textural rhyolite and basalt to andesitic basalt grains are both uncommon but about equal in amount. Most of the polycrystalline quartz grains were eroded from siliceous ashes and flows, but others derive from amygdules and vein fillings of more mafic volcanic rocks. The two origins cannot always be separated petrographically.

Quartz-rich Mode. The clast content of these rare sandstones is made up of subequal amounts of quartz, feldspar (chiefly plagioclase but some orthoclase and very uncommon microcline), and lithic fragments (Fig. 10). Mafic minerals are uncommon, but biotite, epidote, and amphibole are present. Trace heavy minerals include zircon, apatite, tourmaline, and sphene. The lithic clasts consist mostly of textural rhyolite, mosaic quartz, felsite, and siliceous volcanic fragments. A few lithic grains are quartzose sedimentary rock fragments. The quartz-rich mode is dominant in only a few percent of the sandstones of either unit. These beds are concentrated, but *not* exclusively found, at the base of the Yahgan Forma-

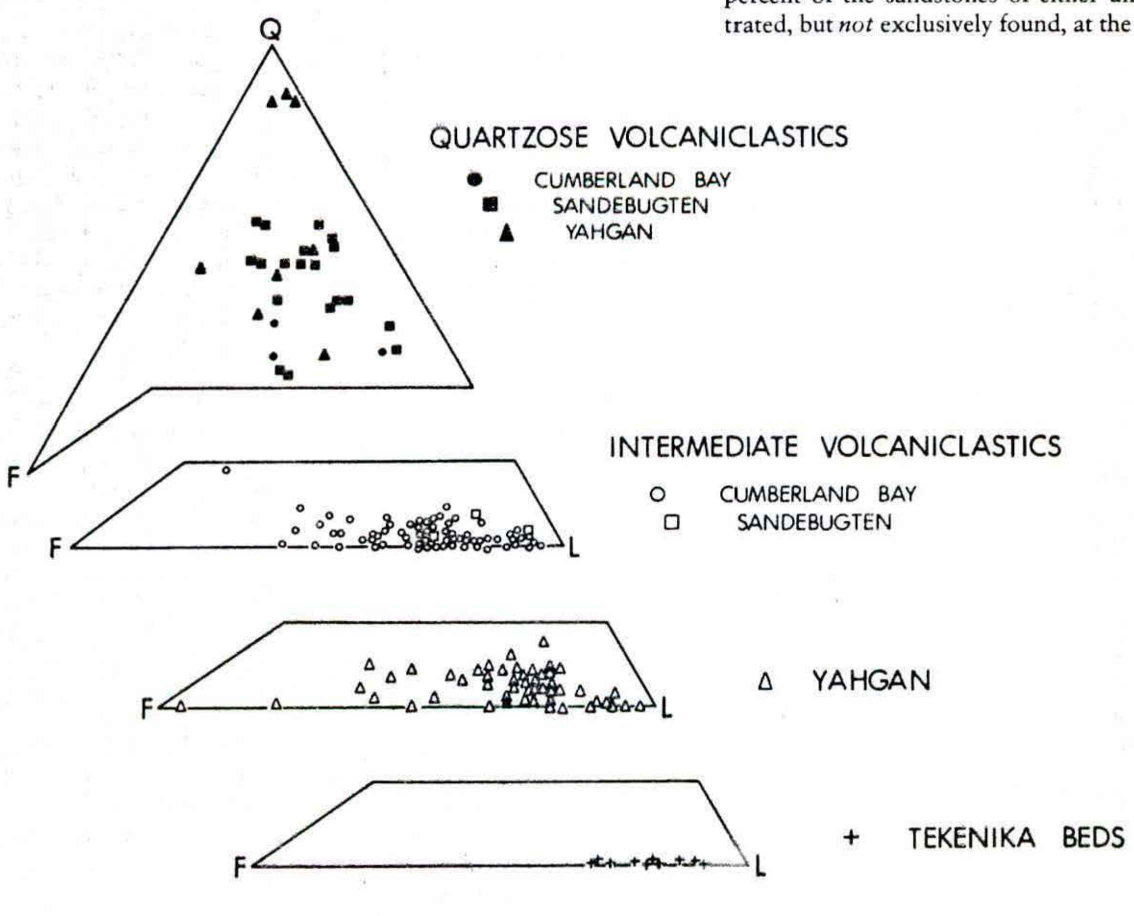

Figure 6. QFL (quartz–feldspar–lithic fragment) diagram of intermediate-volcaniclastic and quartzose sandstones of Yahgan Formation and Tekenika Beds, Tierra del Fuego, and Cumberland Bay and Sandebugten, South Georgia. Diagram constructed from data of Table 1 plus 28 point counts of Cumberland Bay by Skidmore (1972). Skidmore's data were recalculated to exclude his matrix counts from lithic grain category.

tion. In detrital mineralogy, modal abundances, and lithic fragment types, the quartz-rich–mode samples are identical to the Sandebugten sandstones.

SEDIMENTOLOGY AND GENESIS OF SANDEBUGTEN STRATA

Sedimentary structures, fabrics, bedding styles, and trace fossils indicate that the Sandebugten sandstone of South Georgia was deposited by sediment gravity flows in deep water, presumably in a deep-sea fan environment. The unit is composed of evenly stratified alternations of sandstone and slaty mudstone, which appears superficially very much like the Cumberland Bay unit. Most sandstones are graded; all have sediment gravity flow internal fabrics. Sole marks are common (although rarely observed in plan view because of the very strong cleavage in the area), as are flames, mudstone intraclasts, and small scours. The sandstones are all poorly sorted. Only deeper-water trace fossils (such as *Chondrites, Scalarituba)* were observed. The unit is finer grained and more thinly bedded than the Cumberland Bay. Paleocurrent measurements of ripple cross-laminae indicate a bimodal northward and southward pattern, with the southern mode dominant (Fig. 3.)

Petrography

The sandstone clasts are mostly feldspar (chiefly plagioclase), quartz, and lithic fragments (Table 1). It is significant that the QFL plots of the Sandebugten overlap the few quartz-rich modal plots of the Yahgan Formation and Cumberland Bay strata (Fig. 6). Three specimens studied, however, are closer compositionally to the intermediate-volcanic sandstones of the Yahgan and Cumberland Bay.

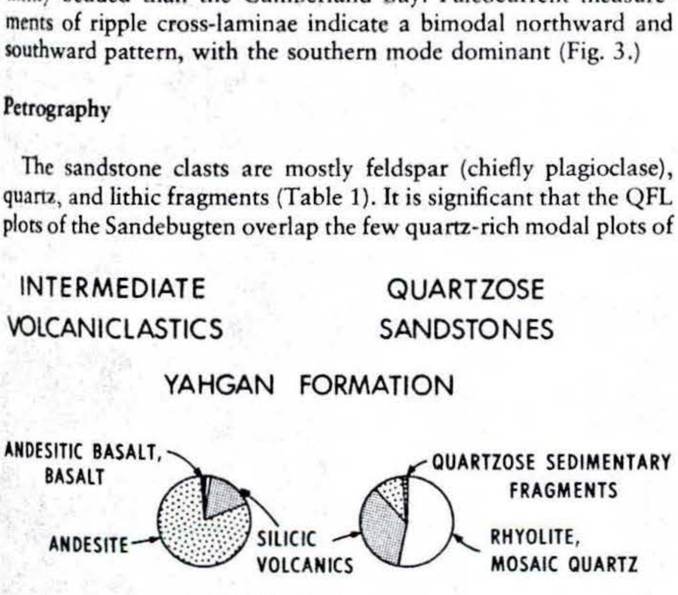

Figure 7. Comparison of relative importance of types of rock fragments within sandstones, and thus relative parent terrane contributions, of Yahgan Formation, Cumberland Bay, and Sandebugten (computed from Appendix Table 4). Textural rhyolite, sericitic grains, and polycrystalline quartz are combined for rhyolite-mosaic quartz group; siliceous volcanic rocks and felsite grains are combined for silicic volcanic group; textural andesite, microlite grains, and andesitic tuff fragments are grouped for andesite class; intersertal, intergranular, and subophitic grains are combined for basaltic andesite to basalt class. Quartzose sedimentary fragments are included in histograms.

None of the Sandebugten outcrops are far removed from the major thrust fault separating the two units on South Georgia, and consequently, all Sandebugten samples are strongly affected by the intensified deformation near that fault. Regardless of the specimen limitations, the petrographic characteristics of the Sandebugten sandstones leave little doubt as to the provenance (see Fig. 11). The only known possible source for the quartz-rich Sandebugten-type sands is the silicic volcanic and sedimentary rocks of the Jurassic Tobifera Formation and equivalents in southern South America. Typically, these Jurassic volcanic rocks are porphyritic. Phenocrysts of quartz and sodic plagioclase and less common potassic feldspar are characteristic; biotite is rare, and pyroxene and amphibole are virtually absent. The quartz and feldspar phenocrysts are characteristically set in a silica or felsite groundmass (Dalziel and others, 1974a). The textural rhyolite, felsite, and "siliceous" volcanic fragments in the Sandebugten sandstone have counterparts in the Tobifera volcanic rocks (compare Figs. 11A, 11B, 11C). Polycrystalline mosaic grains and sericitic fragments in the Sandebugten correspond to groundmass areas in the Jurassic tuffs and flows. Moreover, erosion of such a source would yield sands rich in quartz and plagioclase, low in potassic feldspar, and with few ferromagnesian mineral grains. These are characteristics of the Sandebugten and subordinate quartz-rich sandstones of the Yahgan and Cumberland Bay strata (see Table 1; Figs. 6, 7, 10).

Silicic volcanic rocks exist and may be abundant in intermediate-composition volcanic terranes (for example, the western United States; Lipman and others, 1972). They could be expected in the ancient dacitic-andesitic source that provided almost all of the Yahgan and Cumberland Bay sediments. The large volume and stratigraphic thickness and the uniform composition of the silicic sands of the Sandebugten, however, suggest another origin for this unit. Intermediate volcanic debris forms an insignificant volume (less than 2%) of the Sandebugten sandstone. Moreover, dominant Sandebugten paleocurrent trends are significantly different from Cumberland Bay trends, further suggesting a different source (see Fig. 3). In the reconstructed position of South Georgia southeast of Tierra del Fuego (Fig. 2), the dominant southern paleocurrent mode of the Sandebugten is consistent with a continental South American source.

The presence of quartzose sedimentary fragments in the Sandebugten and in some of the quartz-rich sandstones of the Yahgan and Cumberland Bay strata also argues against derivation of these sands from silicic volcanic rocks interbedded in a dacitic-andesitic terrane. These sedimentary fragments are made up almost entirely of volcanic quartz grains, some grains moderately to well rounded, held together by a phyllosilicate or silica cement (Fig. 10). Plagioclase and silicic volcanic fragments are common constituents. The quartzose sedimentary grains are not first cycle but were derived from existing sedimentary rocks. Their probable source was sedimentary rocks interbedded with the Jurassic silicic volcanic rocks.

Minor microcline and some of the detrital heavy minerals, such as tourmaline, suggest that a very small amount of the Sandebugten-type sandstone was derived from coarser plutonic rocks. This minor contribution could have been either from shallow intrusions associated with the silicic volcanics or from older plutonic rocks underlying the Tobifera.

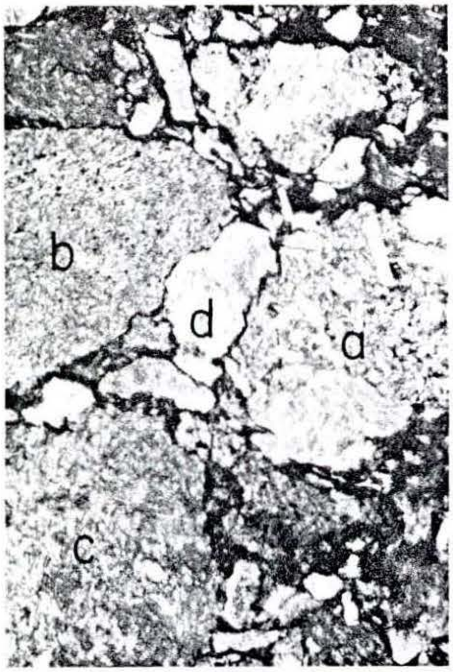

Figure 8. Photomicrograph of typical medium- to coarse-grained volcaniclastic rock of Cumberland Bay strata. Note andesite grain (a), microlitic grain (b), turbid tuffaceous grain (c), angular plagioclase (d), and poor sorting. Compare with Figure 9.

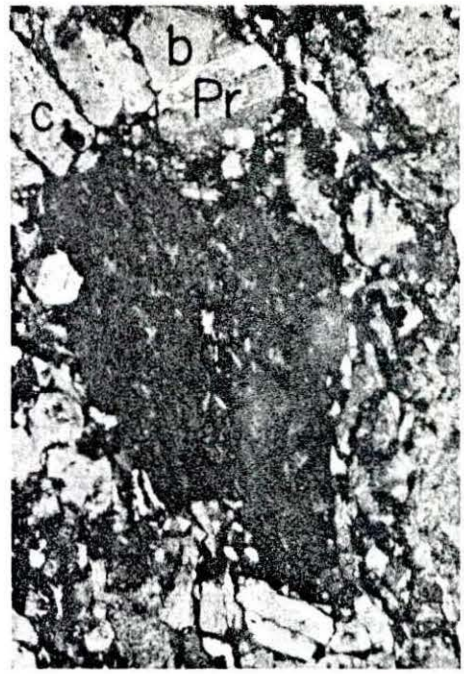

Figure 9. Photomicrograph of typical Yaghan volcaniclastic rock. Note tuff fragment (a), angular plagioclase (b) in andesite grain being replaced by prehnite (Pr), felsite grain (c), and very poor sorting.

DEFORMATION AND METAMORPHISM OF YAHGAN, CUMBERLAND BAY, AND SANDEBUGTEN STRATA

Structural Style

South Georgia Island. Along the island's northeast coast, the South Georgia flysch units are deformed by tight asymmetric folds with planar limbs and narrow hinge zones (see Fig. 3 of Dalziel and others, 1975). The rocks in this area are affected by a very strong axial-planar slaty cleavage. The Cumberland Bay unit verges to the northeast. The Sandebugten rocks verge to the southwest in the thrust area, but axial planes and cleavage swing through the vertical and overturn toward the northeast on Barff Peninsula. Mineral and clast elongation is parallel in both units, and both units have only one major set of structures. Sandebugten and Cumberland Bay strata are interpreted to have been affected by only one period of folding. The fold hinge lines of both sets are approximately parallel to the long dimension of the island. Cleavage and folding die out upward in the Cumberland Bay strata.

Tierra del Fuego. The Yahgan Formation has a similar structural style to the Cumberland Bay. Deformation is very severe north of the Beagle Channel, where the rocks appear to have been thrust an undetermined distance to the north. In this area, the Yahgan is dominated by large-scale, tight, asymmetric folds (see Fig. 4 of Bruhn and Dalziel, 1977), and the rocks show a very strong penetrative cleavage. The folds in the Yahgan are essentially upright or overturned to the north. The fold hinge lines strike east to east-southeast. Folding dies out to the south, as it does in the South Georgia rocks. In the Bahia Tekenika area and southward (see Fig. 4), the rocks are only broadly folded, and cleavage is weak to nonexistent.

Regional Metamorphism

Secondary minerals common to the low-grade Cumberland Bay, Yahgan Formation, and Sandebugten strata are quartz, albite, muscovite, chlorite, epidote, clinozoisite, stilpnomelane, pumpellyite, prehnite, calcite and sphene (see footnote 2 to order Appendix Table 5, Occurrence of Secondary Minerals by Area). Most mineral assemblages correspond to the prehnite-pumpellyite facies (Coombs and others, 1970; Bishop, 1972). Prehnite is very abundant in the Mesozoic flysch of both areas typically associated with and altering to epidote and clinozoisite. Pumpellyite is uncommon. The prevalence of prehnite was one of the observations that first suggested that the Yahgan and Cumberland Bay strata were equivalent (Trendall, 1959; Watters, 1965; Katz and Watters, 1966). The highest grade rocks in Tierra del Fuego and South Georgia are found along the Beagle Canal and at the Cumberland Bay–Sandebugten thrust contact, respectively (Figs. 3, 4). An Fe-poor tremolitic amphibole and garnet occur locally with prehnite in the latter area. Lower-grade heulandite, analcime, laumontite, and an unidentified zeolite are present co-existing with prehnite in samples from southwestern Isla Navarino and southern Isla Hoste. Prehnite

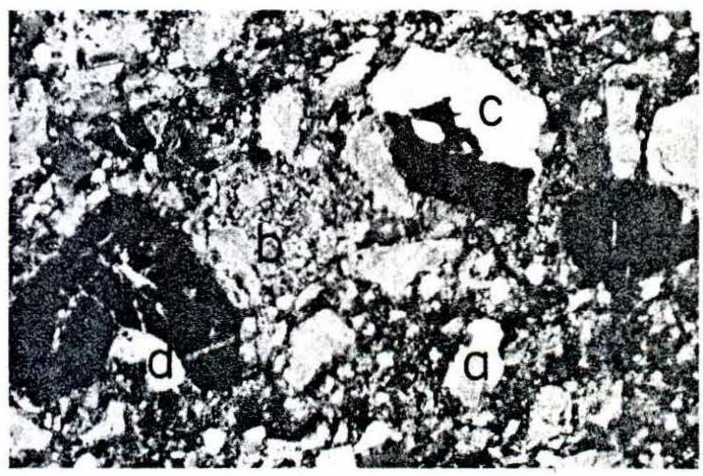

Figure 10. Photomicrograph of Yahgan Formation quartzose volcaniclastic rock collected from western Isla Navarino. Note large amount of quartz, angular plagioclase (a), siliceous volcanic fragment (b), mosaic quartz (c), and terminations and embayments of volcanic quartz crystal (d).

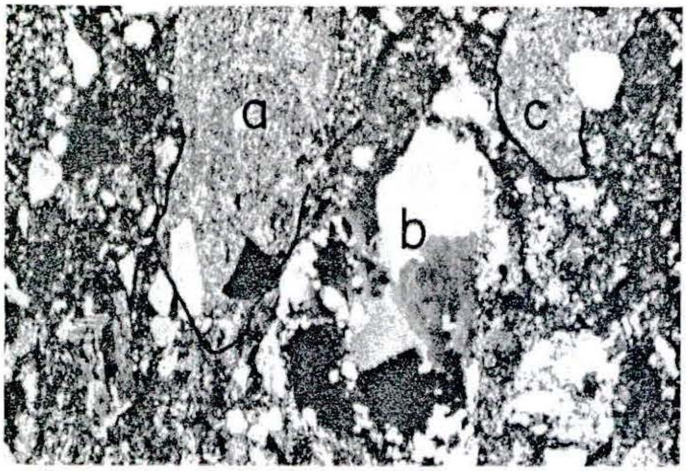

Figure 11A. Photomicrograph of Sandebugten siliceous volcaniclastic rock. Mosaic quartz grain (b) is almost identical to mosaic quartz in Tobifera tuff in Figure 11B (a); sericite groundmass in lithic rocks (c) corresponds to sericitic groundmass of Tobifera tuffs (Fig. 11B, c). Note textural rhyolite fragment (a), angular plagioclase, and poor sorting.

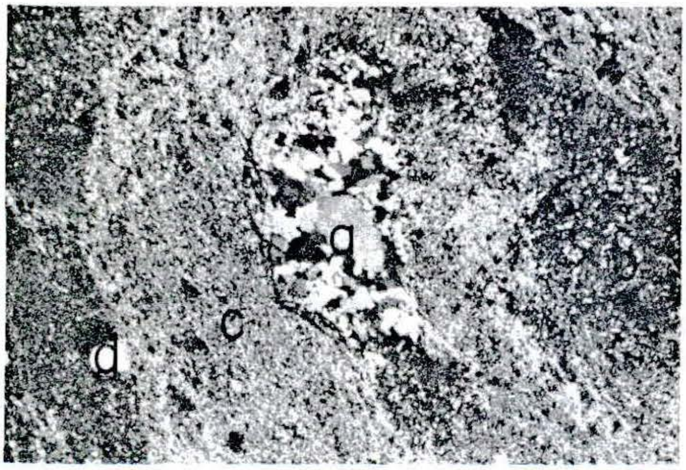

Figure 11B. Photomicrograph of Tobifera Formation tuff sample. Note mosaic quartz (a), felsite area (b), sericitic area (c), and quartz crystals (d).

is absent from heulandite-bearing rocks from Annenkov; the rocks there appear to be a true zeolite facies (also see Winn, 1975).

Because of similar parent compositions and deformation styles, the near-identical metamorphic minerals and associations indicate that generally similar metamorphic conditions existed for the graywackes of both the Yahgan Formation and Cumberland Bay as well as the Sandebugten. In general, it is thought that the prehnite-pumpellyite facies represents an intermediate-pressure–low-temperature type of metamorphism (less than about 5 kb pressure and approximately 200 to 300 °C, according to Bishop, 1972).

PALINSPASTIC RESTORATION

Implications of Tobifera Source for Sandebugten-type Sands

The Yahgan and Cumberland Bay strata have been shown to be stratigraphically equivalent. They have fossils of similar age; their sediments were eroded from similar source terranes — dominantly calc-alkalic volcanic rocks south of their respective depositional areas; both were deposited in deep-sea fan environments; and both

Figure 11C. Photomicrograph of Sandebugten volcaniclastic rock. Note sedimentary fragment (a) and textural rhyolite (b). Felsite grain (c) corresponds to felsite groundmass in Tobifera tuffs (Fig. 11B, b) and flows.

were deformed identically and metamorphosed to the same degree. These are the criteria I set out to demonstrate, but their equivalence does not uniquely prove former juxtapositioning of South Georgia Island and Tierra del Fuego. Intermediate-composition volcanic rocks are very common along long stretches of certain plate margins (for example, the present convergent plate boundary along the western Pacific). Conceivably, sedimentary rocks derived from such volcanics could be quite similar even though they were deposited in widely separated areas. Yet I do infer that South Georgia and Tierra del Fuego were juxtaposed. The most compelling evidence is furnished by the Sandebugten-type sands. There is no source for these sands in the present vicinity of South Georgia; indeed their only known possible source lies in the Jurassic volcanic rocks of Tierra del Fuego or the Antarctic Peninsula. Besides being closer, only the Jurassic volcanics of South America are sufficiently and uniformly siliceous to serve as a source.

Petrographic and stratigraphic evidence confirms the Mesozoic age for the Sandebugten as inferred for structural reasons (see Dalziel and others, 1975). The intermediate-volcaniclastic and siliceous-volcaniclastic rocks interfinger; rare quartzose sands are present on South Georgia within rocks that have Cumberland Bay vergence, and conversely, uncommon intermediate-volcaniclastic rocks are present within the Sandebugten on Barff Peninsula (see Figs. 6 and 7 and Table 1). Sandebugten-like sandstones are concentrated near the base of the Yahgan Formation north of the Beagle Channel, where they make up about 80% of the sandstone specimens collected. Former intermediate tuffs (now prehnite-quartz beds) are interbedded within the quartzose and intermediate-volcaniclastic rocks in this zone. Rare Tobifera-derived sandstones also are scattered throughout the Yahgan Formation on Isla Navarino (see Fig. 10). The paleocurrent directions further suggest that the Isla Navarino and Beagle Channel area was a site of mixing (Fig. 4); the currents are highly dispersed, in contrast to readings taken to the south, and localities with east- and west-trending mean orientations suggest longitudinal fill.

Late Mesozoic Tectonics

Geophysical evidence and the general geologic similarity of southern South America, the Antarctic Peninsula, South Georgia, and the other islands and ridges of the Scotia arc (with the exception of the young volcanic South Sandwich Islands) argues for all of these areas being fragments of a more or less continuous Mesozoic orogenic belt (see Dalziel and Elliot, 1973; Suárez, 1976; De Wit, 1977). Restoration of the Andean–Antarctic Peninsula orogenic belt is accomplished by closure of the Drake Passage. Limited paleogeographic data suggest that bending of South America apparently occurred along northwest- and east-trending transform faults in Tierra del Fuego (Bruhn and Dalziel, 1977). Left-lateral movement along these faults and eastward relative movement of South Georgia are almost certainly genetically related.

The Antarctandes of the Antarctic Peninsula and the Andes developed as a result of convergence first of Gondwanaland and later, after the Atlantic opened (at 125 to 130 m.y. ago or mid-Neocomian time; Larson and Ladd, 1973), of Gondwanaland fragments with Pacific ocean crust (Fig. 12). The silicic volcanic rocks of the Jurassic Tobifera Formation of South America may represent the early stages of subduction and arc formation along the western edge of the continent. Immediately following or during the latter stages of the silicic volcanism, continued east Pacific subduction resulted in fragmentation of the continental margin and the generation of new oceanic sea floor in the rift zones between slivers of basement rocks overlain by the Tobifera Formation.

The Patagonian batholith appears to be the plutonic equivalent of a contemporaneous calc-alkalic volcanic chain in Tierra del Fuego. Although remnants of the volcanic suprastructure are absent, its detritus are preserved in the Yahgan, Cumberland Bay, and Tekenika units. These sediments represent the bulk of the fill of a marginal basin that formed between the active arc and the continent. The Jurassic to Miocene age span of the plutons (Halpern, 1973) overlaps the age of the volcaniclastic rocks and consequently the age span of the former volcanic chain. The volcanic source terrane was made up mostly of dacite and andesite flows and tuffs; more mafic volcanics were very rare. The arc was more siliceous than most ancient and modern calc-alkalic arcs, probably owing to the assimilation of large volumes of continental material. The Patagonian batholith was intruded into a sliver of continental basement (note basement west of the batholith in Fig. 2) and contains large xenoliths of continental rock. The Tierra del Fuego–South Georgia Island segment of the marginal basin was likely never more than about 250 to 300 km wide, because moderately coarse fan sediments derived from each side interfinger, which would not have been possible if the basin edges were far removed. The small basin width also results in the likelihood of continued assimilation of continental crust during development of the arc.

Deposition of the Yahgan and Cumberland Bay volcaniclastic rocks was in a moderately deep-sea environment (Fig. 12). Concurrently, quartz-rich sediment eroded from the Jurassic Tobifera Formation was being deposited in deep-sea fans growing southwestward from the continent. Inferred water depths appear comparable to the oceanic depths of modern marginal basins in the western Pacific (approximately 2.5 to 5.5 km deep; see Karig, 1971).

The volcanic arc was active in the Tierra del Fuego segment until at least middle to early Late Cretaceous (age of the upper part of the Cumberland Bay unit). The Yahgan Formation is overlain concordantly by the Cretaceous Tekenika Beds. The Tekenika sandstones and conglomerates were derived from a source terrane almost identical, although perhaps with a few more exposed plutonic rocks, to the calc-alkalic arc that supplied the detritus of the Yahgan and Cumberland Bay units. The Yahgan Formation, Tekenika Beds, Cumberland Bay, and Sandebugten were deformed by closure of the marginal basin during the Andean Orogeny (Dalziel and others, 1974b). This closure occurred before a late-tectonic pluton, dated at 79± 5 m.y. ago, was emplaced into folded Yahgan Formation rocks (Halpern and Rex, 1972).

The final major convergence phase in Tierra del Fuego appears to have been the collision of the spreading ridge with the continent edge, which probably caused the break-up of the continent and

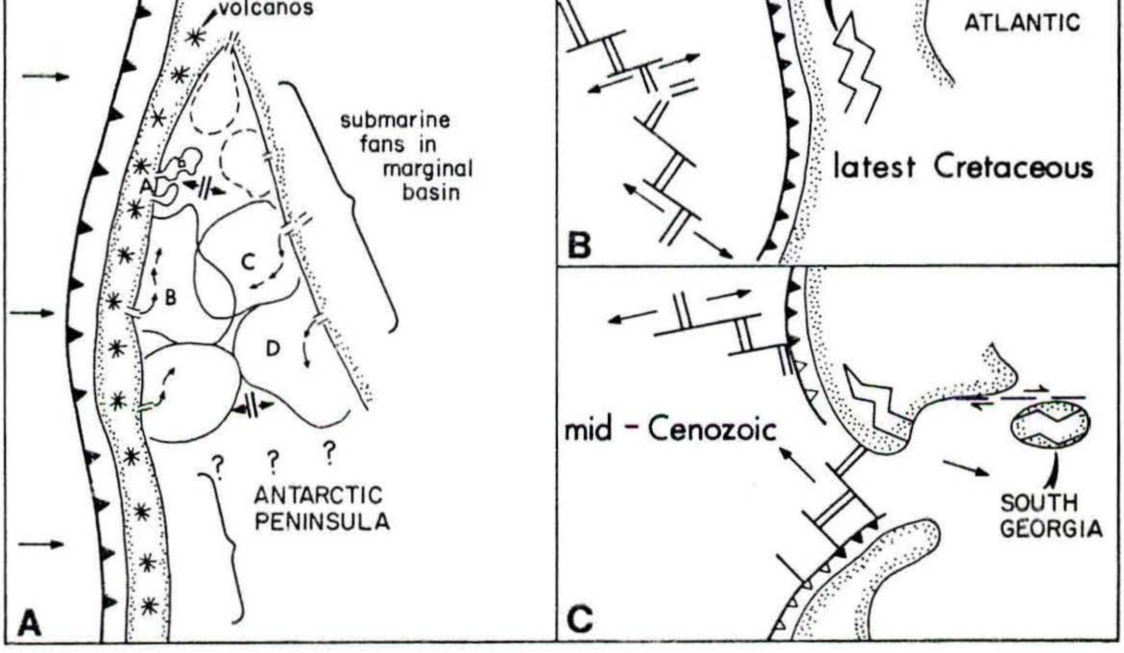

Figure 12. Schematic development of northern Scotia arc. Marginal basin opened in Late Jurassic to Early Cretaceous time and was charactertized by bilateral infilling on deep-sea fans. Fan outlines in A correspond to and have same dimensions as several fans off Oregon and Washington (A is La Jolla–Navy–Coronada fan system; B is Astoria fan; C is Delgada fan, D is Monterey fan). Atlantic opened in Early Cretaceous time. Marginal basin in South America closed by 80 m.y. B.P. By early Cenozoic time (approximately 64 m.y. B.P.) a new ridge system formed in eastern Pacific. South of triple junction this ridge is called Aluk Rise; Chile Rise is descendent of segment north of triple junction. South Georgia microcontinent was translated relatively eastward after ridge-continent collision in mid-Cenozoic time.

formation of the Scotia Sea; this collision profoundly reoriented plate boundaries.

Separation of South Georgia from Tierra del Fuego

The oceanic crust west of southern South America, west of the Antarctic Peninsula, and on the sea floor of the Drake Passage appears to have formed at an active ridge system (Aluk Ridge–ancestral Chile Rise) that originated in Late Cretaceous to Cenozoic time (Herron, 1974; Dott, 1976; Herron and Tucholke, 1976). The oldest sea floor is west of the Antarctic Peninsula and is perhaps as old as 64 m.y. (Fig. 1; approximately the Cretaceous-Cenozoic boundary; Herron and Tucholke, 1976). The Chile Rise is a seismically active northern extension of the former spreading ridge. Magnetic anomalies west of southern South America and west of the Antarctic Peninsula become older away from the respective continents, indicating the overriding of segments of former ridge by continental crust. In both areas, collision of the ridge and trench has drastically slowed or stopped subduction (see Forsyth, 1975). It is not known whether the Drake Passage spreading zone is a direct remnant of the Mesozoic-Cenozoic ridge system or not. Herron and Tucholke (1976) pointed out that the absence of any time overlap between the anomalies west of the Antarctic Peninsula and the Drake Passage anomalies (see Fig. 1) suggests that the ridge segments may not have been part of one continuous system; rather, these ridge segments may have been discrete entities separating small, ephemeral plates. On the other hand, the parallelism of magnetic lineations between these two areas suggests that the ridges are genetically related. The eastward relative movement of South Georgia is postulated to have occurred along a transform fault that leads from the southern edge of Burdwood Bank to the vicinity of the northern edge of South Georgia Island (Wilson, 1966; Barker, 1970; Dott, 1976).

The timing of separation of South Georgia from Tierra del Fuego can be estimated by considering the sea-floor evidence and the timing of events in South America and the Antarctic Peninsula, but definitive evidence is scant. South Georgia and Tierra del Fuego were certainly connected through the period of marginal basin opening and closure. The geology of South Georgia indicates juxtaposition through a late-orogenic period of silicic pluton emplacement (approximately 80 m.y. ago).

On the basis of magnetic lineations, Barker (1970, 1972a, 1972b) estimated the Scotia Sea to be a maximum of 40 m.y. old (Eocene-Oliogene boundary). Because the Scotia Arc apparently owes its inception to the spreading axis–continent collision and dates from the fragmentation of the formerly continuous orogen, this date also suggests the earliest date of separation.[3] The oldest *dated* sea floor in the Scotia Sea is about 20 m.y. old (early Miocene) in the Drake Passage (Fig. 1; Barker, 1970, 1972a, 1972b; Herron and Tucholke, 1976). The separation rates calculated from these two dates (5 to 10 cm/yr) generally correspond to the maximum and minimum spreading rates calculated from the South Pacific (4 to 10 cm/yr; Herron, 1972). An average separation faster than about 10 cm/yr (thus post-Miocene separation of South Georgia) seems unrealistic (Herron, 1972; Dott, 1976).

The structural and stratigraphic evidence from South America and the Antarctic Peninsula supports the above interpretation. Dott (1976) noted that pre-Miocene rocks around the Scotia arc generally show a similar tectonic history, but the later Cenozoic rocks are dissimilar and unconformably overlie the pre-Miocene units. Craddock and Hollister (1976) interpreted a missing Paleocene to late Oligocene or early Miocene section in two Deep Sea Drilling Project holes just west of the Antarctic Peninsula (see Fig. 1) as due to scouring. The disconformity is thought to date inception of the circum-Antarctic current, and hence break-up of the original connection. All available information suggests that separation occurred sometime between early Oligocene and middle Miocene time.

[3] De Wit (1977) has suggested that the sea floor between the South Orkneys and South Georgia is part of the Early Cretaceous marginal basin of South America and that the South Georgia flysch is merely a northern exposure of correlative volcaniclastic rocks that underlie the central Scotia Sea. I do not feel that the evidence supports this interpretation. Paleocurrent data indicate that the Cumberland Bay strata of South Georgia were derived from a southerly source. These deposits are moderately to very coarse fan deposits, so the southerly source had to be fairly close throughout Early Cretaceous time. At most, the central Scotia Sea could be Late Cretaceous and represent a re-opening of the marginal basin after the mid-Cretaceous deformation. The age of the central Scotia Sea, thus, may not indicate the east Pacific ridge-continent collision.

ACKNOWLEDGMENTS

This study was one project in a series of studies of the Scotia arc being undertaken at the University of Wisconsin — Madison in conjunction with Lamont-Doherty Geological Observatory and Columbia University. I appreciate the advice of my co-workers on the study, Ian W. D. Dalziel, Ron L. Bruhn, Maartin de Wit, Margie Winslow, and especially Robert H. Dott, Jr. This study was supported by the Office Programs, National Science Foundation, under grants GV-19543, GV-36656, OPP-21415, and OPP 72-05799 to Dott. I thank P. M. Smith, M. D. Turner, R. L. Dale, and R. Elder for their assistance. Sir Vivian Fuchs provided the opportunity to work on South Georgia. Rikkey Chinn, former Base Commander at South Georgia Island, and the survey personnel on the island were all very helpful. I am grateful to Captain T. Woodfield and the crew of the RRS *Bransfield* for transportation to South Georgia and the officers and crew of the HMS *Endurance* for the return voyage. Captain Norman Deniston and the crew of the R/V *Hero* provided transportation in Tierra del Fuego. The paper was read entirely or in part by R. H. Dott, Jr., I.W.D. Dalziel, C. J. Craddock, C. W. Byers, R. S. Bruhn, and C. V. Guidotti.

REFERENCES CITED

Adie, R. J., 1927, Recent advances in the geology of the Antarctic Peninsula, *in* Adie, R. J., ed., Antarctic geology and geophysics: Oslo, Universitetsforlaget, p. 121–124.

Baker, P. E., 1968, Comparative volcanology and petrology of the Atlantic island arcs: Bull. Volcanol., v. 32, p. 189–206.

Barker, P. F., 1970, Plate tectonics of the Scotia Sea region: Nature, v. 228, p. 1293–1296.

——1972a, A spreading center in the east Scotia Sea: Earth and Planetary Sci. Letters, v. 15, p. 123–132.

——1972b, Magnetic lineations in the Scotia Sea, *in* Adie, R. J., ed., Antarctic geology and geophysics: Oslo, Universitetsforlaget, p. 17–26.

Bishop, D. G., 1972, Progressive metamorphism from prehnite-pumpellyite to greenschist facies in the Dansey Pass area, Otago, New Zealand: Geol. Soc. America Bull., v. 83, p. 3177–3198.

Bruhn, R. L., and Dalziel, I.W.D., 1977 Destruction of the Early Cretaceous marginal basin in the Andes of Tierra del Fuego, *in* Talwani, M., and Pitman, W. C., III, eds., Island arcs, deep sea trenches, and back-arc basins: Am. Geophys. Union. Maurice Ewing symposium, ser. I.

Casey, R., 1961, A monograph of the Ammonoidea of the Lower Greensand, Part 2: London, Palaeontographical Society, p. 45–118.

Chamberlain, C. K., 1971, Bathymetry and paleoecology of Ouachita geosyncline of southeastern Oklahoma as determined from trace fossils: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 34–50.
Coombs, D. S., Horodyski, R. J., and Naylor, R. S. 1970, Occurrence of prehnite-pumpellyite facies metamorphism in northern Maine: Am. Jour. Sci., v. 268, p. 142–156.
Craddock, C., and Hollister, C. D., 1976, Geologic evolution of the southeast Pacific basin, *in* Hollister, C. D., Craddock, C., and others, Initial reports of the Deep Sea Drilling Project, Vol. 35: Washington, D.C., U.S. Govt. Printing Office, 723–743.
Crook, K.A.W., 1960, Petrology of Tamworth Group, Lower and Middle Devonian, Tamworth-Nundle District, New South Wales: Jour. Sed. Petrology, v. 30, p. 353–369.
Curray, J. R., 1956, The analysis of two-dimensional orientation data: Jour. Geology, v. 64, p. 117–131.
Dalziel, I.W.D., 1974, Evolution of the margins of the Scotia Sea, *in* Burk, C. A., and Drake, C. L., eds., The geology of continental margins: New York, Springer-Verlag, p. 567–577.
Dalziel, I.W.D., and Elliot, D.H., 1971, The evolution of the Scotia Arc: Nature, v. 223, p. 246–252.
——1973, The Scotia Arc and Antarctic margin, *in* Nairn, A.E.M., and Stehli, F., eds., The ocean basins and their margins. I. The South Atlantic: New York, Plenum Press, p. 171–245.
Dalziel, I.W.D., Caminos, R., Palmer, K. F., Nullo, F., and Casanova, R., 1974a, The southern extremity of the Andes: Geology of Isla de los Estados, Argentine Tierra del Fugeo: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 2502–2512.
Dalziel, I.W.D., de Wit, M. J., and Palmer, K. F., 1974b, A fossil marginal basin in the southern Andes: Nature, v. 250, p. 291–294.
Dalziel, I.W.D., Dott, R. H., Jr., Winn, R. D., Jr., and Bruhn, R., 1975, Tectonic relations of South Georgia Island to the southernmost Andes: Geol. Soc. America Bull., v. 86, p. 1034–1040.
De Wit, M. J., 1977, The evolution of the Scotia Arc as a key to the reconstruction of southwestern Gondwanaland: Tectonophysics, v. 37, p. 53–81.
Dickinson, W. R., 1969, Evolution of calc-alkaline rocks in the geosynclinal system of California and Oregon: Oregon Dept. Geology and Mineral Industries Bull., v. 65, p. 151–156.
——1970, Interpreting detrital modes of graywacke and arkose: Jour. Sed. Petrology, v. 40, p. 695–707.
——1974, Sedimentation within and beside ancient and modern magmatic arcs, *in* Dott, R. H., Jr., and Shaver, R. H., eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 19, p. 230–239.
Dott, R. H., Jr., 1964, Wacke, graywacke, and matrix — What approach to immature sandstone classification?: Jour. Sed. Petrology, v. 34, p. 625–632.
——1974, Paleocurrent analysis of severely deformed flysch-type strata — A case study from South Georgia Island: Jour. Sed. Petrology, v. 44, p. 1166–1173.
——1976, Contrasts in tectonic history along the eastern Pacific rim, *in* Sutton, G. H., Manghnani, M. H., and Moberly, R., eds., The geophysics of the Pacific Ocean basin and its margin: Am. Geophys. Union Geophys. Mon. 19, p. 299–308.
Dott, R. H., Jr., Winn, R. D., Jr., de Wit, M. J., and Bruhn, R. L., 1977, Tectonic and sedimentary significance of Cretaceous Tekenika Beds of Tierra del Fuego: Nature, v. 266, p. 620–622.
Du Toit, A. L., 1937, Our wandering continents: Edinburgh, Oliver and Boyd, 366 p.
Ewing, J. I., Ludwig, W. J., Ewing, M., and Ettreim, S. L., 1971, Structure of the Scotia Sea and Falkland Plateau: Jour. Geophys. Research, v. 76, p. 7118–7137.
Feruglio, E., 1949, Description geologica de la Patagonia, Vol. 1: Buenos Aires, Direccion General de Yacimientos Petroliferos Fiscales, 334 p.
Forsyth, D. W., 1975, Fault-plane solutions and tectonics of the South Atlantic and Scotia Sea; Jour. Geophys. Research, v. 80, p. 1429–1443.
Griffiths, D. H., and Barker, P. F., 1972, Review of marine geophysical investigations in the Scotia Sea, *in* Adie, R. J., ed., Antarctic geology and geophysics: Oslo, Universitetsforlaget, p. 3–11.
Halpern, M., 1973, Regional geochronology of Chile south of 50° latitude: Geol. Soc. America Bull., v. 84, p. 2407–2422.
Halpern, M., and Rex. D. C., 1972, Time of folding of the Yahgan Formation and age of the Tekenika Beds, southern Chile, South America: Geol. Soc. America Bull., v. 83, p. 1881–1886.
Harrington, H. H., 1943, Observaciones geologicas en la Isla de los Estados: Mus. Argentino Cienc. Nat. Anales, v. 41, p. 29–52.
Hayes, D. E., 1965, The Peru-Chile trench: Canada Geol. Survey Paper 66-15, p. 238–243.
Heezen, B. D., and Johnson, G. L., 1965, The South Sandwich Trench: Deep-Sea Research, v. 12, p. 185–197.
Herron, E. M., 1972, Sea-floor spreading and the Cenozoic history of the east central Pacific: Geol. Soc. America Bull., v. 83, p. 1671–1692.
——1974, Magnetic lineations in the extreme southeast Pacific and their bearing on the evolution of the Scotia arc and Patagonia: Geol. Soc. America Abs. with Programs, v. 6, p. 791.
Herron, E. M., and Tucholke, B. E., 1976, Sea-floor magnetic patterns and basement structure in the southeastern Pacific, *in* Hollister, C. D., Craddock, C., and others, Initial reports of the Deep Sea Drilling Project, Vol. 35: Washington, D.C., U.S. Govt. Printing Office, p. 263–278.
Hoffstetter, R., 1957, Clay-Slate Formation and Yahgan Formation; *in* Lexique stratigraphique international — Amérique latine, Vol. 7, Chile-Paris, Centre National Recherche Scientifique, p. 71–72, 375–377.
Karig, D. E., 1971, Origin and development of marginal basins in the western Pacific: Jour. Geophys. Research, v. 76, p. 2542–2561.
Katz, H. R., 1964, Some new concepts on geosynclinal development and mountain building at the southern end of South America: Internat. Geol. Cong., 22nd, New Delhi 1964, Rept., pt. IV, p. 241–256.
——1972, Plate tectonics — Orogenic belts in the southeast Pacific: Nature, v. 237, p. 331.
Katz, H. R., and Watters, W. A., 1966, Geological investigation of the Yahgan Formation and associated igneous rocks of Navarino Island, southern Chile: New Zealand Jour. Geology and Geophysics, v. 9, p. 232–359.
Larson, R. L., and Ladd, J. W., 1973, Evidence for the opening of the South Atlantic in the Early Cretaceous: Nature, v. 246, p. 209–212.
Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1972, Cenozoic volcanism of the western United States. I. Early and middle Cenozoic: Royal Soc. London Philos. Trans., ser. A, v. 271, p. 217–248.
Ludwig, W. L., Ewing, J I., and Ewing, M., 1968, Structure of Argentine continental margin: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 2337–2368.
Mathews, D. H., 1959, Aspects of the geology of the Scotia Arc: Geol. Mag., v. 96, p. 425–440.
Middleton, G. V., and Hampton, M. A., 1973, Sediment gravity flows: Mechanisms of flow and deposition, *in* Turbidites and deep-water sedimentation: Soc. Econ. Paleontologists and Mineralogists Pacific Sec. Short Course, p. 1–38.
Mutti, E., 1974, Examples of ancient deep-sea fan deposits from circum-Mediterranean geosynclines, *in* Dott, R. H., Jr., and Shaver, R. H., eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 19, p. 92–105.
Natland, M. L., P. Gonzalez, E., Cañon, A., and Ernst, M., 1974, A system of stages for correlation of Magallanes Basin sediments: Geol. Soc. America Mem. 139, 126 p.
Nelson, C. H., and Kulm, L. D., 1973, Submarine fans and deep-sea channels, *in* Turbidites and deep-water sedimentation: Soc. Econ. Paleontologists and Mineralogists Pacific Sec. Short Course, p. 39–78.
Normark, W. R., 1974, Submarine canyons and fan-valleys: Factors affecting growth patterns of deep-sea fans, *in* Dott, R. H., Jr., and Shaver, R. H., eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 19, p. 56–68.
Pettigrew, T. H., and Willey, L. E., 1975, Belemnite fragments from Annenkov Island: British Antarctic Survey Bull., no. 40, p. 33–36.
Skidmore, M. J., 1972, The geology of South Georgia: III, Prince Olav Harbour and Stromness Bay areas: British Antarctic Survey Sci. Rept., no. 73, 50 p.
Stepanicic, P. N., 1967, Consideraciones sobre las edades de algunas faces magmaticas del Neopaleozoico and Mesocoico: Geol. Argentina Rev., v. 22, p. 101–133.
Stepanicic, P. N., and Reig, O., 1955, Breve noticia sobre el hallazgo de anuros en el denominado Complejo Porfirica de la Patagonia extra-Andina con consideraciones acerca de la composicion geologica del

mismo: Asoc. Geol. Argentina Rev., v. 10, p. 215–233.

Stone, P., and Willey, L. E., 1973, Belemnite fragments from the Cumberland Bay type sediments of South Georgia: British Antarctic Survey Bull., v. 36, p. 129–132.

Suárez, M., 1976, Plate tectonic model for southern Antarctic Peninsula and its relation to southern Andes: Geology, v. 4, p. 211–214.

Suárez, M., and Pettigrew, T. H., 1976, An upper Mesozoic island-arc–back-arc system in the southern Andes and South Georgia: Geol. Mag., v. 113, p. 305–328.

Trendall, A. F., 1953, The geology of South Georgia — I: Falkland Islands Dependencies Survey Sci. Rept. 7, 26 p.

——1959, The geology of South Georiga — II: Falkland Islands Dependencies Survey Sci. Rept. 19, 48 p.

Van der Plas, L., and Tobi, A. C., 1965, A chart for judging the reliability of point counting results: Am. Jour. Sci., v. 263, p. 87–90.

Watters, W. A., 1965, Prehnitization in the Yahgan Formation of Navarino Island, southernmost Chile: Mineralog. Mag., v. 34, p. 517–527.

Wilckens, O., 1933, Der Südantillen Bogen: Geol. Rundschau, v. 24, p. 320–335.

——1937, Geologishche Ergebrisse der Deutschen Süd-Georgien Expedition 1928–29: Geol. Rundschau, v. 28, p. 127–128.

——1947, Palaeontologische und geologische Ergebrisse der eise von Kohl-Larsen (1928–29) nach Süd-Georgien: Senckenberg. Natur. Gesell. Abh., v. 474, p. 1–66.

Wilson, J. T., 1966, Are the structures of the Caribbean and Scotia Arc regions analogous to ice rafting?: Earth and Planetary Sci. Letters, v. 1, p. 335–338.

Winn, R. D., Jr., 1975, Late Mesozoic flysch of Tierra del Fuego and South Georgia Island: A sedimentologic approach to lithosphere plate restoration [Ph.D. thesis]: Madison, Univ. Wisconsin — Madison, 160 p.

Winn, R. D., Jr., and Dott, R. H., Jr., 1975, Deep-water conglomerates and breccias of late Mesozoic age in Chilean Tierra del Fuego: Am. Assoc. Petroleum Geologists and Soc. Econ. Paleontologists and Mineralogists Ann. Mtg. Abs., v. 2, p. 82.

——1976, Submarine fan sedimentation in Mesozoic arc–rear marginal basin in southern South America [abs.]: Am. Assoc. Petroleum Geologists Bull., v. 60, p. 734.

——1977, Submarine-fan turbidites and resedimented conglomerates in a Mesozoic arc–rear marginal basin in southern South America, *in* Stanley, D. J.,and Kelling, G. K., eds., Sedimentation in submarine canyons, fans, and trenches: Stroudsberg, Pa., Dowden, Hutchinson, & Ross.

Manuscript Received by the Society May 20, 1976
Revised Manuscript Received April 21, 1977
Manuscript Accepted May 5, 1977