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INSIDE

On the Organization of American Plates in the Neoproterozoic and the Breakout of Laurentia

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ABSTRACT

Laurentia, the Precambrian core of the North American continent, is surrounded by late Precambrian rift systems. Within the supercontinent of Pangea, North America therefore constitutes a "suspect terrane" because its origin as a discrete continent and geographic location prior to the late Paleozoic are uncertain. Students of South American geology have long recognized evidence for the presence of a "southeast Pacific continent" to the west of the present Andean margin throughout the early to mid-Paleozoic. A geometric and geologic fit can be achieved between the Atlantic margin of Laurentia and the Pacific margin of the Gondwana craton. The reconstruction places the Labrador-Greenland promontory of Laurentia within the Arica reentrant of Gondwana. The enigmatic Arequipa massif along the southern Peruvian coast, yields ca. 2.0 Ga radiometric ages and is thereby juxtaposed with the Makkovik-Ketilidian province of the same age range in Labrador and southern Greenland. In the reconstruction, the ca. 1.0 Ga Grenville belt continues beneath the ensialic Andes of the present day to join up with the 1.3–1.0 Ga San Ignacio and Sonsas-Aguapei orogens of the Transamazonian craton.

Together with the recent identification of possible continuations of the Grenville orogen in East Antarctica and of the Taconic Appalachians in southern South America, the fit supports and refines suggestions that Laurentia broke out from between East Antarctica–Australia and embryonic South America during the Neoproterozoic, prior to the opening of the Pacific Ocean basin and amalgamation of the Gondwana supercontinent. This implies that there may have been two supercontinents during the Neoproterozoic, before and after opening of the Pacific Ocean. It therefore calls to question the existence of so-called supercontinental cycles. The basic configuration of some continental nuclei may have changed little since the Neoproterozoic, despite extensive tectonic modification of their margins. The Arica bight of the present day may reflect a primary embayment in the South American continental margin that controlled subduction processes along the Andean margin and eventually localized uplift of the Altiplano.

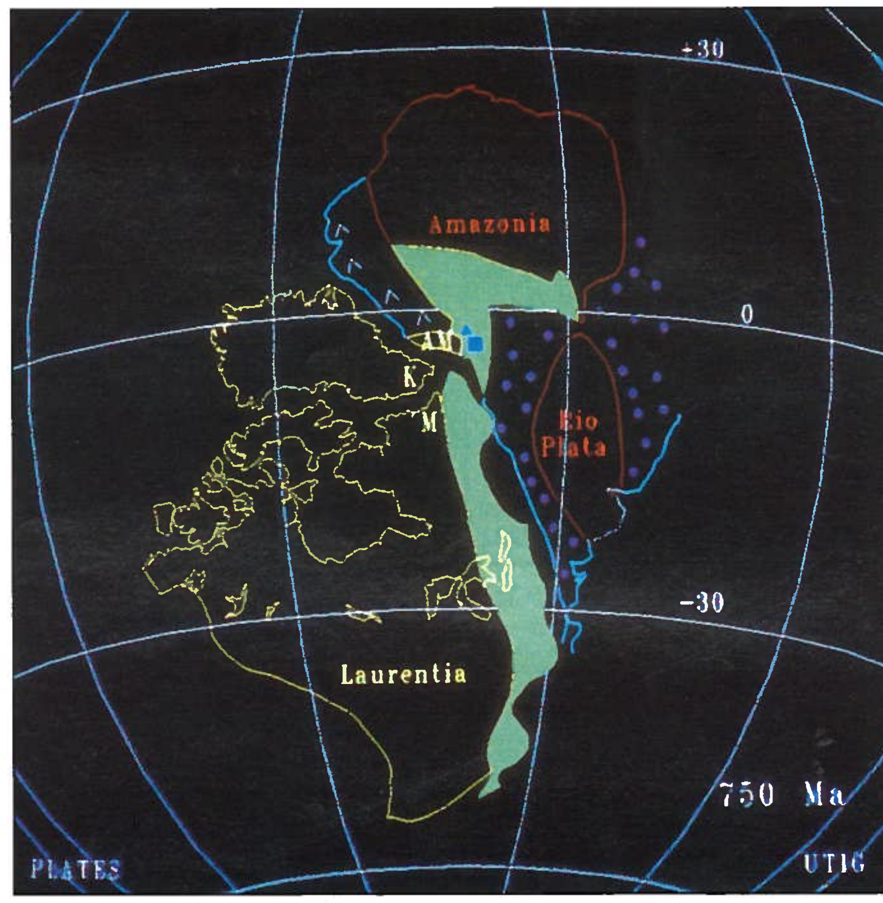

Figure 1. Computer reconstruction (orthographic projection) of the relation between the Laurentian craton (gold) and the South American part of the Gondwana craton (blue) proposed for the Neoproterozoic (ca. 1.0 Ga–550 Ma). The reconstruction is shown in an arbitrary reference frame close to that of present-day South America with small circles of latitude at 30° intervals intended for scale only. Green indicates the extent of the Grenville orogen in Laurentia (from Hoffman, 1989) and its suggested continuation into South America. Amazonian and Rio del Plata cratonic nuclei (red) and Pan-African belts (purple stipple) in South America are after Teixeira et al. (1989); locally the present-day Andes (white chevrons) completely obscure the basement. AM—Arequipa massif; K—Ketilidian province; M—Makkovik province; square—Belén province; triangle—San Andres No. 2 well.

LAURENTIA

The ancestral core of the North American continent was assembled by collisional tectonic processes by ca. 1.0 Ga (Hoffman, 1988). However, although the location of North America on Earth's surface can be convincingly established as far back as the Mesozoic opening of the Atlantic Ocean basin on the basis of marine geophysical data (Klitgord and Schouten, 1986), the origin of Laurentia as a discrete continent has remained obscure because it is surrounded by Neoproterozoic to Cambrian rift systems (Hoffman, 1989). Within Pangea it is a "suspect terrane" of uncertain prior geographic position (Coney et al., 1980). Conventionally, Laurentia has been positioned opposite northwest Africa in Paleozoic reconstructions, reflecting J. Tuzo Wilson's question: "Did the North Atlantic open, close, and then reopen?" (Wilson, 1966). It has also been conventional to restore the Appalachian margin of the Laurentian craton against northwestern Africa in late Precambrian reconstructions (e.g., Hatcher, 1989). There is, however, no firm geologic evidence for this reconstruction, and paleomagnetic data afford no longitudinal control. Thus, alternative reconstructions are permissible as long as they can account for observations such as the distribution of Avalonian rocks along the margins of North America, Europe, and Africa and the presence of Rokelide(?) basement and fossiliferous Paleozoic cover beneath the coastal plain of northern Florida (Hatcher et al., 1989). The rifted counterpart of the Pacific margin of the Laurentian craton is also obscure. Sears and Price (1978) suggested rifting from part of Siberia during the mid-Proterozoic. Bell and Jefferson (1987) drew attention to the similarity of the Neoproterozoic strata of western Canada and eastern Australia and suggested that they had been juxtaposed at that time, although no reconstruction of the cratons themselves was presented.

One of the linchpins of Du Toit's reconstruction of the Gondwana supercontinent prior to the opening of the southern oceans was the truncation of the early Mesozoic Cape fold belt at the Atlantic margin of southern Africa, and its apparent continuation in the Sierra de la Ventana that is truncated along the Atlantic margin of South America (Du Toit, 1937). The truncation of the Appalachian and Caledonian orogens along the margins of the North Atlantic provide similar evidence in support of Mesozoic separation of North America and Europe (Holmes, 1945; Kay, 1969). The termination of the Grenville orogen of Laurentia at the Labrador margin also appears to be explained by the presence of the Sveco-Norwegian province of the same age in the Baltic craton, although the connection through northern Britain is somewhat tenuous (Gower and Owen, 1984; Gower et al., 1990). In contrast, the termination of the Grenville and adjoining Yavapai-Mazatzal orogens at the Pacific margin of the Laurentian craton has lacked an obvious explanation, despite the presence of some Grenvillian-age rocks in northwestern South America (Dengo, 1985). Recently, however, Moores (1991) broke new ground by presenting a reconstruction with the East Antarctic–Australian craton juxtaposed with that of Laurentia in the Neoproterozoic. Dalziel (1991) supported this with a computer reconstruction and identified a possible counterpart for the Yavapai–Mazatzal–Grenville boundary, the Grenville front, near the head of the Weddell Sea embayment. These developments led to new theories regarding the configuration of a possible Neoproterozoic supercontinent (Dalziel, 1991, 1992; Hoffman, 1991).

Another potential "piercing point" (Crowell, 1959) along the margin of the Laurentian craton is provided by the southern termination of the Appalachian orogen. The effects of the collision of Laurentia with Africa to form Pangea are visible in the Ouachita orogeny and the terminal Alleghanian event of the Appalachian orogenic revolution (Hatcher et al., 1989), although the main Appalachian mountain range and the Ordovician structures of the Taconic orogen disappear southwestward beneath the Gulf of Mexico coastal plain. Again, until recently, this apparent truncation and the "hole" in the North American continent represented by the Ouachita embayment have remained unexplained. Dalla Salda et al. (1992a, 1992b) have suggested that the continuation of the Taconic orogen is to be found in the Famatinian belt of South America and possibly even farther south in the Shackleton Range of East Antarctica. Thus, several lines of evidence point to the possibility that, within Pangea, North America was an "exotic terrane" of intra-Gondwanian affinities that had traveled nearly 10 000 km along the proto-Andean margin of South America during the Paleozoic (Dalziel, 1991, Fig. 2; Dalziel et al., 1992).

GONDWANA

The North American affinities of the Precordilleran terrane that borders the present-day Andes of northwestern Argentina has been known for many years (Borrello, 1971; Ross, 1975; Ramos et al., 1986). Its Cambrian-Ordovician carbonate platform contains the Pacific realm Olenellid trilobite fauna of Walcott (1889). The presence of this fauna, and determi-

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nation of a thermal subsidence curve that indicates rift-drift transition close to the Precambrian-Cambrian boundary, led Bond et al. (1984) to suggest that the proto-Appalachian and proto-Andean margins were juxtaposed in the late Precambrian. Recently Hoffman (1991) and I (Dalziel, 1991, 1992) used the same criteria, and the presence of a 1.3–1.0 Ga "Grenvillian"-age orogen on the western margin of the Transamazonian craton, to put forward similar hypotheses that Laurentia originated between East Antarctica–Australia and the Precambrian cratons of embryonic West Gondwana prior to the Neoproterozoic opening of the Pacific Ocean basin and amalgamation of the Gondwana supercontinent. The Paleozoic Famatinian belt, however, intervenes between the Precordilleran terrane and the Gondwana craton. Therefore, Dalla Salda et al. (1992b) have suggested that the carbonate platform was part of the interior of the Laurentian craton that was detached from the Ouachita embayment following collision with the South American margin of Gondwana during the Ordovician Taconic-Ocloyic (i.e., early Famatinian) orogeny (Dalla Salda et al., 1992a). Hoffman (1992) and I (Dalziel, 1992) both believe, on the basis of time-space considerations, that western Laurentia must have separated from the Pacific margin of East Antarctica–Australia in mid-Proterozoic (Windermere-?Beardmore) time. Paleomagnetic data indicate that Laurentia may have stayed close to the proto-Andean margin of South America during the late Precambrian opening of the Pacific Ocean basin and amalgamation of the Gondwana supercontinent, and during the Paleozoic (Dalziel, 1991, Fig. 2; 1992). Thus, the "south-east Pacific continent" that students of South American geology have for many years considered to have lain off the Andean margin of Gondwana during the Paleozoic (e.g., Dalmayrac et al., 1980) may have been Laurentia.

A LAURENTIA–SOUTH AMERICA FIT

The Appalachian margin of Laurentia has well-developed promontories and reentrants that are believed to reflect the configuration of the craton margin following Neoproterozoic rifting (Williams, 1964; Thomas, 1977, 1991; Hatcher et al., 1989). The most obvious promontory along the margin of the Laurentian craton, however, is located at the northern termination of the Appalachian orogen. I shall refer to this as the Labrador-Greenland promontory (Fig. 1). Although the present-day margin of southeastern Greenland resulted from Mesozoic rifting of Europe from North America, the presence of the craton margin in northwesternmost Scotland and central East Greenland indicates that this promontory must have been at least as pronounced at the end of the Precambrian as it is today. There is considerable similarity between the geology of the Baltic craton and that of northeastern Labrador and Greenland. Thus, in late Precambrian reconstructions, Baltica is usually restored to a position adjacent to the Labrador-Greenland promontory with an adjustment of relative orientation (Gower and Owen, 1984; Gower et al., 1990), although this is not necessarily the pre-Iapetus position. There is no reason why another, geologically similar, cratonic area could not have intervened.

The late Precambrian proto-Andean margin of the Amazonian craton can be identified in northernmost Argentina (Fig. 1). The Neoproterozoic to Lower Cambrian Puncoviscana Formation mainly comprises turbidites derived from the craton (Aceñolaza et al., 1988; Jezek et al., 1985), but it also contains shallow-water sedimentary strata with fossils comparable to those found in the southwestern United States (Aceñolaza and Durand, 1986). There is, therefore, despite limited exposure of the basement and overprinting by Andean orogenesis, evidence that these rocks may represent the remnants of a late Precambrian margin.

Tracing the Pacific limit of this margin yields what may be a critical clue to its origin. To the south it forms the boundary between Rio de la Plata craton and the Paleozoic Famatinian orogen (Dalla Salda et al., 1992a). To the north and west lies the Arequipa massif along the coastline of southern Peru that has puzzled students of Andean geology for many years. Located immediately to the north of the prominent Arica bight in the present-day continental margin, the Arequipa massif comprises high-grade metamorphic rocks (granulite facies) that yield radiometric dates on the order of 2.0 Ga (Cobbing et al., 1977; Dalmayrac et al., 1977). Its presence outboard of the Andean Cordillera has led several authors to suggest that it may constitute an exotic terrane that collided with South America, thereby contributing to orogenic uplift of the Cordillera in general and the Altiplano in particular (e.g., Nur and Ben-Avraham, 1982). Stratigraphic evidence, however, indicates that the Arequipa massif has been in essentially its present position along the Andean margin since the late Precambrian to early Paleozoic (Forsythe et al., 1992), and the Cordillera appears to be ensialic (Dalmayrac et al., 1980). The ca. 2.0 Ga rocks therefore appear to constitute part of the Transamazonian craton. The reentrant in the craton at the bight in the present-day continental margin may therefore be a feature dating back to its inception during late Precambrian to earliest Paleozoic rifting (see Dewey and Lamb, 1992).

Juxtaposition of the Atlantic margin of the Laurentian craton with the Pacific margin of the South American craton using the PLATES software of the Institute for Geophysics of the University of Texas at Austin shows that the Labrador-Greenland promontory is the correct size and shape to have rifted from the Arica reentrant (Fig. 1). Moreover, the reconstruction indicates that the Arequipa massif could be explained as a segment of the Makkovik-Ketilidian province of Labrador and southern Greenland (Hoffman, 1989; Gower et al., 1990). The Grenville province of Laurentia could have continued beneath the ensialic Andean Cordillera of the present day to join up with the 1.3–1.0 Ga San Ignacio and Sonsas-Aguapei orogens that border the Transamazonian cratonic nucleus (Litherland et al., 1985; Teixeira et al., 1989). These in turn could have been continuous with the Sveco-Norwegian province of Baltica (Fig. 2). Precambrian rocks have been found at two localities within the Andean Cordillera immediately to the east of the Arequipa massif. Rocks from the Belén massif of northernmost Chile and from a borehole in the Bolivian Altiplano have yielded ages of ca. 1.0 Ga (Lehmann, 1978; Pacci et al., 1981). Despite uncertainty regarding the significance of the result from the Belén rocks, a broadly "Grenvillian" age seems likely (Baeza and Pichowiak, 1988). Thus a candidate for the continuation of the Grenville front can be located within the Arica

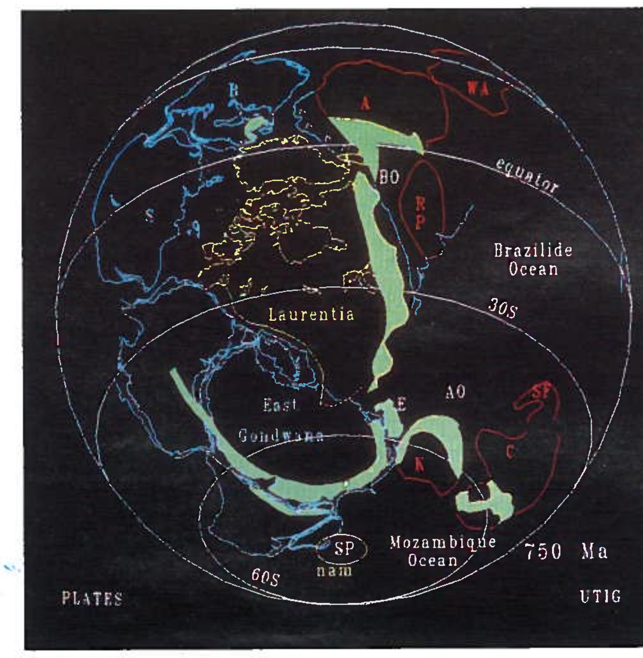

Figure 2. Reconstruction (orthographic projection) of the early to mid-Neoproterozoic supercontinent suggested to have assembled in the Grenvillian orogeny (ca. 1.3–1.0 Ga), prior to opening of the Pacific Ocean basin (~750 Ma). The relative positions of Laurentia, East Gondwana, the cratons of West Gondwana (red), and Baltica (B) are as discussed in this paper and in Dalziel (1992). The position of Siberia (S) relative to Laurentia follows Hoffman (1991). The supercontinent is shown in the reference frame a of paleomagnetic pole for Laurentia (SP = South Pole) of Park et al. (1989) determined from diabase dated by U-Pb (zircon) at 777 Ma in the Mackenzie Mountains, Northwest Territories, Canada. The gold small circle (nam) is the circle of confidence at the 95% level for this pole. Green indicates the extent of the Grenville orogen and its possible continuations. Gold A—Arequipa massif. Red letters: A—Amazonia, C—Congo craton, K—Kalahari craton, RP—Rio de la Plata craton, SF—São Francisco craton, WA—West African craton. White letters: AO—Adomaster Ocean (Hartnady et al., 1985), BO—possible additional Brazilide Ocean, E—Ellsworth-Whitmore mountains block of West Antarctica.

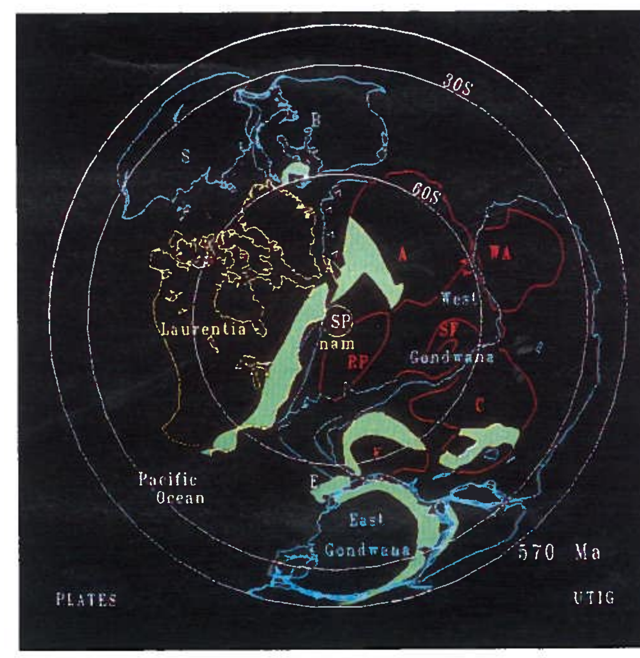

Figure 3. Reconstruction (orthographic projection) of the supercontinent suggested for the latest Precambrian (~570 Ma) following opening of the Pacific Ocean and amalgamation of Gondwana, but prior to opening of southern Iapetus (see Dalziel, 1992; Dalziel et al., 1992). The supercontinent is shown in the reference frame of the paleomagnetic pole (SP = South Pole) determined by Symons and Chiasson (1991) for the Callendar alkalic complex of Ontario dated by the K-Ar and Pb-Pb methods at 575 Ma. The gold small circle (nam) is the circle of confidence at the 95% level for this pole. Other letter designations as for Figure 2.

reentrant opposite the equivalent piercing point on the Labrador-Greenland promontory of Laurentia (Fig. 1).

IMPLICATIONS

The geometric and geologic match of the Atlantic margin of the Laurentian craton and the Pacific margin of the South American craton constitutes additional evidence in support of the hypothesis that Laurentia originated between East Gondwana and the several cratons of West Gondwana (Moores, 1991; Dalziel, 1991, 1992; Hoffman, 1991). Thus, an early Neoproterozoic supercontinent (Fig. 2), assembled during the 1.3–1.0 Ga Grenvillian interval, may have included the Amazonian, West African, and Rio de la Plata cratons as well as Laurentia, Siberia, Baltica, East Gondwana, the Kalahari craton, and (possibly) the Congo–São Francisco craton.

As mentioned above, time and space considerations suggest that the Transantarctic–eastern Australian margin separated from Laurentia to open the Pacific Ocean basin at the time the Windermere passive margin developed during the mid-Neoproterozoic (Ross, 1991; Dalziel, 1992; Hoffman, 1992). However, stratigraphic data from western Newfoundland (Williams and Hiscott, 1987) indicate that, despite evidence of rifting along the Appalachian margin of the Laurentian craton at about that time (Hatcher et al., 1989), the rift-drift transition did not take place there until the earliest Cambrian (ca. 540 Ma; Compston et al., 1992) when thermal subsidence began (Bond et al., 1984; Bond and Kominz, 1991). As Gondwana appears to have amalgamated by about 600 Ma (see Dalziel, 1992, for discussion), a further implication of the proposed fit of the Labrador-Greenland promontory and the Arica reentrant is that Laurentia and Gondwana formed part of a different supercontinent in the late Neoproterozoic after the opening of the Pacific Ocean basin (Fig. 3).

This possibility needs to be taken into account in considering the envi-

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ronmental changes that took place at the end of the Precambrian, and the emergence of multicellular organisms. The paleomagnetic poles from Laurentian rocks used to position the supercontinents in the reconstructions for 750 and 570 Ma (Figs. 2 and 3) are in keeping with the suggestion of Park (1992) that Laurentia may have moved across the South Pole near the Precambrian-Cambrian boundary. Two supercontinental assemblies during the Neoproterozoic in approximately the paleolatitudes shown, separated by the opening of the Pacific Ocean basin and the amalgamation of Gondwana, may help to explain the time-space distribution of glacial deposits formed during that interval (Chumakov and Elston, 1989). The hypothesis of a regular "supercontinental cycle" (Murphy and Nance, 1992; Turcotte and Kay, 1992; Hartnady, 1993), is called into question by the reconstructions, especially because Laurentia broke away from the late Neoproterozoic supercontinent soon after it had formed, and seems to have reunited with Gondwana three times during its Paleozoic journey around the proto-Andean margin of Gondwana (Dalla Salda et al.,1992a, 1992b; Dalziel et al., 1992). Amalgamation of several cratons to form supercontinents from time to time seems inevitable on the surface of a dynamic Earth of constant radius (Duncan et al., 1992).

A further implication of the proposed fit is that, despite significant modification of their margins as a result of Phanerozoic tectonism, the discrete cratons that separated during the Neoproterozoic were very robust entities indeed. For example, if the Labrador-Greenland promontory and the Arica reentrant are related as suggested here, the present-day Arica bight originated in a latest Neoproterozoic to earliest Paleozoic rift event (see Dewey and Lamb, 1992). Knowledge of the growth of the South Atlantic Ocean basin precludes major modification of the eastern margin of South America during the Mesozoic and Cenozoic. Paleomagnetic data suggest movement of small blocks along the Pacific margin into the Arica bight during the Mesozoic and Cenozoic (Beck, 1988), but there are no data to suggest that the bend in the Andean Cordillera there is secondary. Thus, the basic shape of the bight may be inherited from rifting of the Labrador-Greenland promontory of Laurentia from the Arica reentrant of Gondwana at a triple junction with a failed arm that formed the Paleozoic ensialic orogen between the Arequipa massif and the cratonic nucleus of Amazonia (Fig. 1; Dalmayrac et al., 1980). In that case the Altiplano may owe its existence to that ancient extensional event and to the consequent modification of Phanerozoic tectonic processes by the presence of the reentrant (Isacks, 1988; Scanlan and Turner, 1992).

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