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Erosion of Great Escarpments

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ABSTRACT

Compilation of geological, geophysical, structural, and geochronological data suggests that the location and morphologic character of great escarpments bordering continental rifts and passive margins are pre determined by crustal structure and argue against the accepted paradigm of on-going, significant parallel retreat. Escarpments, although not retreating uniformly, increase in sinuosity over time as embayments retreat more rapidly than interfluves. Generally, escarpments located along structurally uplifted and warped margins *(arch-type)* are breached by large drainage systems originating inland from the escarpment and are more sinuous than those located along simply uplifted margins *(shoulder-type)* suggesting the major importance of pre-rift drainage systems to the erosion of great escarpments. However, a weak correlation between the degree of sinuosity and escarpment age suggests that the process by which sinuosity increases is complex. Thus, age and the overall structure of the margin control the pattern and tempo of erosion along great escarpments, while other parameters such as lithology, local structural variability, and climate are less important.

INTRODUCTION

The world’s great escarpments are located in two distinct tectonic and morphologic environments: along continental rift margins and along continental passive margins (Fig. 1). These two environments are related. Continental rifts express the first stages of crustal extension; ocean basins represent the later. The continuous tectonic process by which continental rifts mature into passive margins led to the assumption that morphologies also evolve through a continuous process, specifically escarpment retreat. The concept of steady parallel escarpment retreat of 100's of km is embedded in the descriptions of rift margin development (e.g. King, 1955; Partridge and Maud, 1987; Tucker and Slingerland, 1994; Seidl et al., 1996; Widdowson and Cox, 1996). Recently, the idea of substantial escarpment retreat along rift margins has been questioned in southern Africa (Cockburn et al., 2000; Fleming et al., 1999).

Following previous studies (Ollier, 1984; van der Beek and Braun, 1999; Gilchrist and Summerfield, 1994; Beaumont et al., 2000), we divide escarpments into two types depending on whether the drainage divide is coincident with the top of the escarpment (*shoulder-type margins*) or separated from it (*arch-type margin*; Fig. 1). Along shoulder-type margins, changes in location of the top of the escarpment are accompanied by the migration of the drainage divide. Along arch-type margins, escarpment retreat is not accompanied by a change in the location of the drainage divide. Furthermore, since the drainage divide is located in the low relief region of the plateau above the escarpment it is relatively stationary (Gilchrist et al., 1994; Nott and Horton, 2000). Drainages flowing into the rift from a shoulder-type margin, although steep, have very restricted watersheds and thus limited ability to cut headword either fluvially or by groundwater-induced sapping. However, when headword retreat does occur, both the escarpment and the divide shift. Conversely, along arch-type margins drainages, many of which are antecedent to rifting, have bigger catchments, higher discharges, greater stream power that enable faster embayment of the escarpment.

In this paper, we synthesize geochronologic, geophysical, and structural data with morphometric analysis to elucidate better the pattern and tempo of escarpment development. The combined data sets cast doubt on the concept of major and continuous escarpment retreat along rift and passive margins and suggest the major importance of crustal structure in determining the location and morphological development of escarpments.

METHODS

Using a single set of topographic maps at a scale of 1:5,000,000,we measured sinuosity (Bull and McFadden, 1977) of twenty-four escarpments that border continental rift and passive margins[1] (Fig. 1). Map scale plays a major role in determining sinuosity. The degree of sinuosity generally increases with an increase in map scale (see foot-note 1). We chose a scale that detects sinuosity caused only by major escarpment-breaching

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[1] GSA Data Repository item XXX, Table 1, Table 2, Additional references, is available on request from Document Secretary, GSA, P.O.Box 9140, Boulder, CO 80301-9140, editing@geosociety.org or at www.geosociety.org/pubs/ftXXXX.htm.

drainage systems in order to highlight the relation between degree of sinuosity and the margin's structure.

PATTERN OF MARGIN EROSION

The style and rate at which escarpments erode depends on the processes and energy available for movement of material. For example, Weissel and Seidl (1998) and Seidl et al. (1996) show that escarpment retreat in southeast Australia is dominated by episodic mass wasting except within channels, where knick-point retreat is rapid. Extremely high knick point retreat rates (2 km My^{-1}; Weissel and Seidl, 1998) compared with low retreat rates along escarpment interfluves (7 to 53 m My^{-1}; Heimsath et al., 2000), suggest escarpment sinuosity increases with time. Because escarpments retreat faster in places where streams are active than along the rate of sinuosity increase depends directly on the number of large drainage systems that originate inland and breach the escarpment. The frequency and size of escarpment breaching drainages is related to the margin's structure and to the drainage system that was active prior to rifting

CONTINENTAL RIFT MARGINS

A relation between structure, morphology, and drainage pattern is observed along young and older continental rifts. Continental rift escarpments are formed by normal faults and are located directly above or very close to them (e.g. Heimann, 1990;

Hutchinson et al., 1992). For example, the Dead Sea Fault system separats the Arabian plate from the Sinai sub-plate. A series of normal faults form escarpments bounding a narrow rift valley. The activity along the Dead Sea has been continuous from the early Miocene to the present (e.g. Garfunkel, 1988; Ellenblum et al., 1998). However, morphologic expression of the rift valley started only in late Miocene-early Pliocene (Garfunkel, 1970; Gerson et al., 1984). Shoulder-type and arch-type margins appear on both sides of the rift valley at different locations (Wdowinski and Zilberman, 1997). The location of the drainage divide is determined by the margin's structure (Picard, 1943; Matmon et al., 1999). Where the margin is arched, the drainage divide is located away from the rift valley and the escarpment embayment process is controlled by antecedent drainage systems that predate the rift's development. Where the margin is of the soulder-type, the drainage divide coincides with top of the escarpment. Normal faults are observed at the escarpment's base. There is no evidence for significant escarpment retreat.

Similar structural-topographic relations are observed along older continental rifts. Both types of margins (shoulder and arch) are identified along the western brach of the East African Rift and the Baikal Rift (Bloom, 1998; Hutchinson et al., 1992). The drainage pattern along the margins of the rift follows the structure, long rivers on the arched side and short ones on the shoulder side. There is no evidence for substantial retreat of escarpments away from the normal faults that formed them. Fission track data from continental rifts, such as the southern Dead Sea Rift and the East African Rift, yielded ages that generally do not correspond to the rifting event but rather to older phases of the cooling history of the sampled rocks (Kohn and Eyal, 1981; van den Haute, 1984; see foot-note 1).

PASSIVE MARGINS

The tectonic history and morphologic development of passive margins is obscured by the passage of time. However, structural and morphological features are similar to those found along continental rifts. Both arch and shoulder-type margins can be identified. Along shoulder-type margins (such as the Western Ghats and the eastern Brazil coastal escarpment) drainage systems are short and steep and the top of the escarpment coincides with the main drainage divide. Along typical arch-type escarpments (such as southeast Australia), the drainage divide is located inland from the top of the escarpment, the drainage systems are long, and the escarpment is sinuous.

A spatial correspondence between passive margin escarpments and gravimetric and magnetic anomalies suggests the relation between crustal structure and escarpment location implying that crustal, rather than surfacial process, control escarpment location. For example, along the Western-Ghats, India, gravimetric and magnetic anomaly bands are located directly below the escarpment suggesting the relation between the location of the escarpment and deep crustal structure (Kalaswad, 1993; see foot-note 1). Such a correlation exists also in south east Australia (Webb et al., 1998) and in Namibia, where magnetic anomaly bands spatially correlate with escarpment location and are absent where a defined escarpment is absent (http://www.gsn.gov.na/magnetics.htm; 5/01). The proximity of old passive margin escarpments and structural discontinuities suggests that escarpments are relatively stationary (Judson, 1975; Young, 1989; Kalaswad, 1993).

Fission track ages seaward of passive margin escarpments correlate to the initiation of sea floor spreading and are younger than those inland of the escarpment implying significant denudation by rapid retreat or by down-wearing below the escarpment (see foot-note 1). It is apparent that sufficient unloading occurred during escarpment erosion to cause this general difference in fission track ages. Rapid erosion following sea floor spreading and subsequent stabilization of great escarpments is also supported by U-Th/He dating in south-east Australia (Persano et al., 2001) and sedimentary sequences in ocean basins adjacent to the passive margins (e.g. Rust and Summerfield, 1990; van der Beek and Braun, 1999). If continuous and substantial escarpment retreat had occurred since rifting, fission track ages should decrease along the coastal plain towards the escarpment (Ollier and Pain, 1997); a trend not observed.

The escarpment stability indicated by fission track data, which integrate rates of erosion over tens of millions of years, is supported by cosmogenic nuclide data that integrate erosion and thus escarpment retreat rates over 10^5-10^6 years (see foot-note 1). Fleming et al. (1999) estimated rates of cliff retreat on the South African escarpment at

50-95 m My^{-1}, while Bierman and Caffee (2001) calculated mass loss equivalent to an erosion rate of 16 m My^{-1} from a basin that drains the Namibian escarpment. These rates are two orders of magnitude less than that implied by consistent, parallel escarpment retreat imposed on landscape models of the Namibian escarpment (King, 1962; Tucker and Slingerland, 1994). Estimated denudation rates of only several m My^{-1}, both below and above the southwestern African escarpments, indicate exceptional landscape stability and suggest that differential erosion between the plateau above the escarpments and the coastal plain below, the other means by which to generate current topography, is not currently occurring (Cockburn et al., 2000; Bierman and Caffee, 2001). All available geochronological data from passive margins (see foot-note 1), argue against continuous parallel retreat of great escarpments.

ESCARPMENT SINUOSITY

Sinuosity and margin age are imperfectly correlated, probably reflecting the complex contribution of age, over all margin's structure, and local lithologic and structural conditions (e.g. van der Beek et al., 2001). Continental rifts with shoulder-type margins have low sinuosity values; arch-type margins present a wide range of sinuosity values although generally higher than those of the shoulder-type margins (Fig. 2). The difference results from antecedent drainage systems that flow across arch-type rift escarpments enabling faster knick-point retreat (e.g. Seidl et al., 1996; Bloom, 1998; Nott and Horton, 2000). Arch-type passive margins have a narrow range of high sinuosity values. Shoulder-type margins exhibit a wide range of sinuosity values (Fig. 2).

Sinuosity measurements indicate that age and structure control escarpment sinuosity. The higher sinuosity of arch vs. shoulder-type margins (along both rifts and passive margins) suggests that margin structure influences escarpment's sinuosity. Margin structure determines the frequency of escarpment-breaching, and thus sinuosity inducing, drainage systems. The role of age in determining the escarpment sinuosity is shown by the difference between the average sinuosity ($\pm 1\sigma$) of older (65 to 160 Ma) passive margin escarpments and younger (0 to 27 Ma) continental rift escarpments (2.8 ± 0.7 (n=7) and 1.8 ± 0.8 (n=11), respectively.

CONTINENTAL RIFT – PASSIVE MARGIN TRANSFORMATION

The rapid transformation from rifted to passive margins can be viewed along the Red Sea and the Gulf of Aden, where sea floor spreading initiated only a few million years ago (Bohannon et al., 1989; Steckler and Omar, 1994). Along the western and eastern margins of the Red Sea escarpments, where they do exist, are located tens to hundreds of kilometers from the coast. Fission track data from the Red Sea show the spatial pattern characteristic of passive margins (Omar and Steckler, 1995; Fig. 2). These observations indicate that although the Red Sea is a young ocean, the escarpments that accompany it are more similar to escarpments located along passive margins than to those of continental rifts. A reasonable assumption is that the Red Sea margins, before sea floor spreading initiated, were similar to other continental rifts. As soon as sea floor spreading initiated, rapid erosion occurred and it took only 5-10 million years for the rift escarpments to erode significantly.

IMPLICATIONS

Considered together, the different data sets suggest stages through which Great Escarpments evolve. Escarpments develop along normal faults formed at continental rift margins. Over time, these escarpments erode and become more sinuous as knick points retreat rapidly along drainage systems that cross the escarpment. Large antecedent basins above the escarpment along arch-type margins enable a more rapid increase in sinuosity compared to the slow increase that occurs along shoulder-type margins. This pattern is best illustrated by considering escarpment pairs: the western and the eastern margins of the Dead Sea rift (12 and 13; Fig. 1), the western and eastern margins of Lake Baikal (17 and 19; 18 and 20; Fig. 1), and the western and eastern margins of Lake Albert (5 and 6; Fig. 1). Nevertheless, rift margins do not retreat significantly from their original location determined by the normal faults that formed them.

When sea floor spreading initiates, erosion rates increase dramatically due to base level lowering as shown by fission track and U-Th/He data and sedimentary sequences in off shore basins adjacent to some great escarpments. Original rift escarpments diminish quickly, as exemplified along the Red Sea, and erosional escarpments develop (Gilchrist et al., 1994). These erosional escarpments, which are the great escarpments of continental passive margins, probably grow more sinuous with time. However, due to their antiquity, the correlation between age and degree of sinuosity is weak; they are all highly sinuous. The close spatial relations between some of the largest passive margin escarpments and the location and trends of gravimetric and magnetic anomalies suggests that great escarpment location is controlled by deep crustal structure (e.g. Young, 1989; Kalaswad, 1993). Thus, the data suggest that stable rift escarpments erode rapidly during and immediately after sea floor spreading and a new stable escarpment that accompanies the passive margin is developed.

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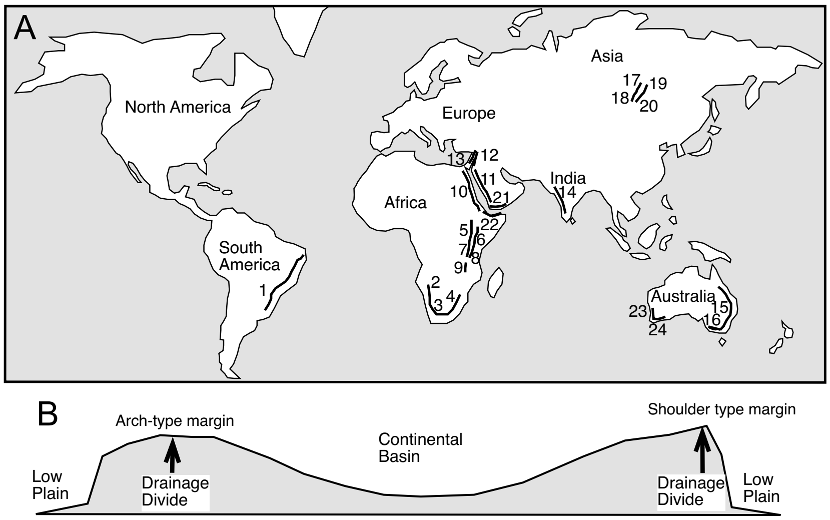
FIGURE CAPTIONS

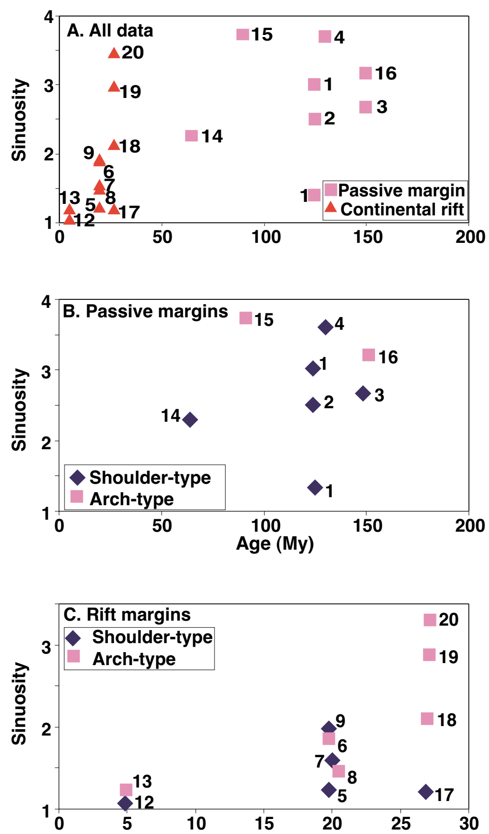
Figure 1. A: Location of major escarpments along rifted and passive continental margins. Escarpments indicated by black lines. Modified from Kooi and Beaumont (1994). Numbers refer to data points in figure 2. B: Generalized continental margin geometry modified from Ollier (1984). *Arch-type* margins are defined as margins where the top of the escarpment and the main drainage divide do not coincide. *Shoulder-type* margins are defined as margins where the top of the escarpment and the main drainage divide coincide.

Figure 2. Relationship of escarpment sinuosity and average age of rifting. Sinuosity is ratio of escarpment length at base to chord length digitized from a single set of maps (*The world Series, 1:5000000, U.S. Army Topographic Command, Series 1106*). Repeated measurements indicate a maximum error of ± 3.5% in the measurement procedure and an average error of ± 1% (n=28). Numbers correlate

to escarpments shown in Figure 1. Note the difference in scale between A,B and C.



Matmon et al., Fig. 1



Matmon et al., Fig. 2

Data Repository 1 – Matmon et al.

TABLE 1. ESCARPMENT SINUOSITY

Name	Scale	Begin point	End point	Base of escarpment (cm)*	Chord (cm)†	Ratio§	Age (Myr)#	Contour (a.m.s.l)**	Structure (margin type) ††	Stage§§	Source##
SW Australia											
	1:2500000	121°45'E 33°45'S	116°15'E 34°30'S	44.56	22.90	1.95	40	150	Arch	Passive	Fairbridge and Finkel, 1978
	RM			42.86	23.10	1.85	40		Arch	Passive	
	1:2500000	116°05'E 34°28'S	114°08'E 27°35'S	75.94	33.09	2.30	160	150		Passive	
	RM			76.09	32.52	2.34	160		Arch	Passive	
	1:6400000			10.50	7.10	1.48	40	200	Arch	Passive	
Somalia											
	1:5000000	49°45'E 11°30'N	42°25'E 11°30'N	30.16	17.39	1.73	20	500	N.D.	Transition	Cochran, 1981
	RM			29.28	16.38	1.79	20		N.D.	Transition	
	1:6400000	49°45'E 11°30'N	42°25'E 11°30'N	16.19	11.59	1.40	20	500	N.D.	Transition	
Yemen											
	1:5000000	50°50'E 15°15'N	43°40'E 13°00'N	29.05	16.28	1.78	20	500	N.D.	Transition	Cochran, 1981
	RM			29.22	16.29	1.79	20		N.D.	Transition	
	1:6400000	50°50'E 15°15'N	43°40'E 13°00'N	17.12	12.49	1.37	20	500	N.D.	Transition	
Saudi Arabia											
	1:5000000	43°40'E 13°00'N	35°00'E 28°30'N	81.96	39.40	2.08	20	500	N.D.	Transition	Ommar and Steckler, 1995
	RM			79.37	38.81	2.05	20		N.D.	Transition	
	1:2000000	40°20'E 21°35'N	43°45'E 13°35'N	78.11	48.67	1.60	20	500	N.D.	Transition	
	1:4000000	43°40'E 13°00'N	35°00'E 28°30'N	99.03	47.69	2.08	20	500	N.D.	Transition	
	1:6400000	43°40'E 13°00'N	35°00'E 28°30'N	15.80	10.60	1.49	25	500	N.D.	Transition	

TABLE 1 (CONT.)

Name	Scale	Begin point	End point	Base of escarpment (cm)*	Chord (cm)†	Ratio§	Age (Myr)#	Contour (a.m.s.l)**	Structure (margin type) ††	Stage§§	Source##
Egypt and Sudan											
	1:5000000	40°15'E 12°10'N	37°35'E 18°00'N	20.86	13.70	1.52	20	500	N.D.	Transition	Ommar and Steckler, 1995 Bohannon et al., 1989
	RM			20.57	14.23	1.44	20		N.D.	Transition	
		37°10'E 18°25'N	35°10'E 23°00'N	29.27	10.38	2.82	20	500	N.D.	Transition	
	RM			28.30	10.91	2.59	20		N.D.	Transition	
		35°00'E 23°30'N	32°50'E 28°50'N	17.04	12.41	1.37	20	500	N.D.	Transition	
	RM			16.66	12.42	1.34	20		N.D.	Transition	
	1:5600000	40°15'E 12°10'N	32°50'E 28°50'N	8.20	8.10	1.01	20	500	N.D.	Transition	
Israel											
	1:5000000	35°00'E 29°30'N	35°30'E 33°20'N	9.34	7.84	1.19	5	200	Arch	Rift	Wdowinski and Zilberman, 1997; Garfunkel, 1981; Ginat etal., 1998; Nir, 1970
	RM			9.40	7.84	1.20	5		Arch	Rift	
	1:6400000	35°00'E 29°30'N	35°30'E 33°20'N	11.30	10.90	1.04	5	200	Arch	Rift	
Jordan											
	1:5000000	35°00'E 29°30'N	35°30'E 33°20'N	8.38	7.86	1.07	5	200	Shoulder	Rift	Wdowinski and Zilberman, 1997
	1:5000000	35°00'E 29°30'N	35°30'E 33°20'N	8.25	7.94	1.04	5		Shoulder	Rift	
	1:6400000	35°00'E 29°30'N	35°30'E 33°20'N	10.20	9.90	1.03	5	200	Shoulder	Rift	
Namibia											
	1:5000000	12°30'E 17°10'S	17°00'E 27°52'S	68.10	26.60	2.56	125	1000	Shoulder	Passive	Brown et al., 2000
	RM			63.62	26.32	2.42	125		Shoulder	Passive	
	1:6400000	12°30'E 17°10'S	17°00'E 27°52'S	28.60	13.80	2.07	125	1000	Shoulder	Passive	

TABLE 1 (CONT.)

Name	Scale	Begin point	End point	Base of escarpment (cm)*	Chord (cm)†	Ratio§	Age (Myr)#	Contour (a.m.s.l)**	Structure (margin type) ††	Stage§§	Source##
South Africa											
	1:5000000	17°10'E 28°05'S	20°05'E 33°45'S	113.23	30.65	3.69	130	500	Shoulder	Passive	Brown et al., 2000; Fleming et al., 1999
		31°15'E 27°30'S	20°11'E 33°50'S	39.87	14.90	2.68	150	500	Shoulder	Passive	
East Africa											
	1:5000000	33°50'E 09°30'S	34°30'E 15°30'S	24.74	12.85	1.92	20	1000	Shoulder	Rift	Bloom 1998)
		29°00'E 02°45'S	31°00'E 08°50'S	21.61	13.94	1.55	20	1000	Shoulder	Rift	
		29°05'E 02°45'S	31°05'E 08°40'S	19.99	13.49	1.48	20	1000	Arch	Rift	
		31°15'E 03°45'N	29°15'E 00°23'S	12.44	10.22	1.22	20	1000	Shoulder	Rift	
		32°15'E 03°40'N	29°30'E 00°45'S	21.17	11.17	1.90	20	1000	Arch	Rift	
	1:6400000	29°00'E 02°45'S	31°00'E 08°50S	12.60	9.50	1.33	20	1000	Shoulder	Rift	
		29°05'E 02°45'S	31°05'E 08°40'S	10.70	10.00	1.07	20	1000	Arch	Rift	
		31°15'E 03°45'N	29°15'E 00°23'S	7.30	6.50	1.12	20	1000	Shoulder	Rift	
		32°15'E 03°40'N	29°30'E 00°45'S	17.40	9.40	1.85	20	1000	Arch	Rift	
SE Australia											
	1:2500000	145°30'E 37°45'S	149°30'E 37°30'S	43.36	14.76	2.94	150	305	Arch	Passive	Ollier and Pain, 1997; Young, 1983
		149°30'E 37°30'S	152°25'E 27°35'S	137.88	49.00	2.81	90	305	Arch	Passive	
	1:5000000	145°30'E 37°45'S	149°30'E 37°30'S	26.20	8.05	3.25	150	200	Arch	Passive	
		149°30'E 37°30'S	152°25'E 27°35	87.83	23.13	3.80	90	200	Arch	Passive	
	1:5000000	145°30'E 37 °45'S	149°30'E 37°30'S	25.69	8.34	3.08	150	200	Arch	Passive	
		149°30'E 37°30'S	152°25'E 27°35'S	84.09	23.01	3.65	90	200	Arch	Passive	
	1:6400000	145°30'E 37°45'S	149°30'E 37°30'S	21.00	12.80	1.64	90	200	Arch	Passive	

TABLE 1 (CONT.)

Name	Scale	Begin point	End point	Base of escarpment (cm)*	Chord (cm)†	Ratio§	Age (Myr)#	Contour (a.m.s.l)**	Structure (margin type) ††	Stage§§	Source##
<u>India</u>											
	1:2000000	77°30'E 08°10'N	76°25'E 10°25'N	40.10	14.12	2.84	65	300	Shoulder	Passive	Kalaswad, 1993
		76°47'E 10°45'N	73°50'E 16°20'N	91.13	34.38	2.65	65	300	Shoulder	Passive	
		73°40'E 21°10'N	73°55'E 16°10'N	86.14	30.42	2.83	65	300	Shoulder	Passive	
	1:5000000	77°30'E 08°10'N	76°25'E 10°25'N	11.30	6.21	1.82	65	200	Shoulder	Passive	
		76°47'E 10°45'N	73°50'E 16°20'N	30.19	13.70	2.20	65	200	Shoulder	Passive	
		73°40'E 21°10'N	73°55'E 16°10'N	30.45	11.15	2.73	65	200	Shoulder	Passive	
	1:6400000			36.00	24.80	1.45	65	200	Shoulder	Passive	
<u>Brazil</u>											
	1:1000000	46°45'W 24°05'S	44°25'W 22°55'S	59.02	27.32	2.16	125	200	Shoulder	Passive	Brown et al., 2000
	1:5000000	46°45'W 24°05'S	44°25'W 22°55'S	7.16	5.19	1.38	125	200	Shoulder	Passive	
		50°15'W 29°35'S	46°30'W 24°00'S	45.90	15.32	3.00	125	200	Shoulder	Passive	
	1:6400000	46°45'W 24°05'S	44°25'W 22°55'S	5.41	4.23	1.28	125	200	Shoulder	Passive	
		50°15'W 29°35'S	46°30'W 24°00'S	34.12	11.49	2.97	125	200	Shoulder	Passive	
<u>Baikal</u>											
	1:2500000	110°20'E 56°08'N	106°30'E 53°00'N	26.18	17.05	1.54	27	800	Shoulder	Rift	Logatchev and Zorin, 1992 Hutchinson et al., 1992
		106°25'E 52°55'N	105°50'E 51°45'N	29.50	6.50	4.54	27	800	N.D.	Rift	
		110°25'E 55°50'N	109°00'E 53°30'N	31.93	11.46	2.79	27	800	Arch	Rift	
		107°10'E 51°55'N	103°30'E 51°30'N	42.31	7.92	5.34	27	800	Arch	Rift	
	1:5000000	110°20'E 56°08'N	106°30'E 53°00'N	7.64	6.39	1.20	27	1000	Shoulder	Rift	
		106°25'E 52°55'N	105°50'E 51°45'N	7.94	3.72	2.13	27	1000	N.D.	Rift	
		110°25'E 55°50'N	109°00'E 53°30'N	11.87	3.99	2.98	27	1000	Arch	Rift	
		107°10'E 51°55'N	103°30'E 51°30'N	13.43	3.87	3.47	27	1000	Arch	Rift	

Note: All the escarpments were digitized at a scale of 1:5000000. Where maps were available, escarpments were digitized at scales between 1:1,000,000 to 1:6,400,000 to examine the importance of map scale. Calculation of average sinuosity were done considering only results from 1:5000000 maps.

RM - Repeated measurements.

N.D. = not determined.

*Digitized distance from begin-point to end-point along contour.

†Digitized chord distance from begin-point to end-point.

§Ratio between * and †.

#Average age of rift development.

**Digitized contour between begin-point to end-point.

††Margin's over all structure.

§§Margin's development stage.

##Source of age and structure information.

TABLE 2. SUMMARY OF GEOLOGICAL, GEOPHYSICAL, AND CHRONOLOGICAL DATA FOR EROSION OF GREAT ESCARPMENTS

Name	Margin type (Margin stage)	Fission track and (U-Th)/He ages (My)	Comments and reference	Cosmogenic data (m My^{-1})	Comments and reference	Geophysical evidence	Geological evidence	Age (My)	Reference (structure and age)
Somalia									
	(Transition)	N.D.		N.D.		N.D.	N.D.	20	Cochran, 1981
Yeman									
	(Transition)			N.D.		N.D.	N.D.	20	Cochran, 1981
Saudi Arabia									
	Arch (Transition)	22-237 ave. 40 on the coast 13.8-568	Generally young and uniform ages on coastal plain and older on upland	N.D	Omar and Steckler, 1995; Bohannon, 1989	N.D.	N.D.	20	Ommar and Steckler, 1995
Egypt and Sudan									
	Shoulder (Transition)	22-237 (Average of 40 on the coast)	Generally young and uniform ages on coastal plain and older on upland	N.D	Omar and Steckler, 1995;	N.D.	N.D.	20	Ommar and Steckler, 1995 Bohannon, et al., 1989
		13.8-568 (south east part of Red Sea)	Most ages older than rifting No correlation with elevation.		Bohannon, 1989				
		9-277 (Sinai)			Kohn and Eyal, 1981				

TABLE 2(CONT.)

Name	Margin type (Margin stage)	Fission track and (U-Th)/He ages (My)	Comments and reference	Cosmogenic data (m My^{-1})	Comments and reference	Geophysical evidence	Geological evidence	Age (My)	Reference (structure and age)
Israel									
	Arch (Rift)	N.D.		N.D.		N.D.	Normal faults at base of escarpment suggesting insignificant retreat	5	Wdowinski and Zilberman, 1997
Jordan									
	Shoulder (Rift)	N.D.		N.D.		N.D.	Normal faults at base of escarpment suggesting insignificant retreat	5	Wdowinski and Zilberman, 1997
Namibia									
	Shoulder (Passive)	70-160	FT ages are not correlated with elevation but generally younger on coastal plain than on upland. (Brown et al., 2000)	5 (granite inselbergs) 5-8 (granite inselbergs) 15 (mass removal from escarpment)	(Bierman and Caffee, 2001; Cockburn et al., 1999) Measured from sediments in drainages on the escarpment	Magnetic anomalies parallel and below escarpment. Magnetic anomalies perpendicular to coast where there is no escarpment (http://www.gsn.gov.na/magnetics.htm)	Erosion around major intrusions suggests a minimum denudation rate of 7-15 m My^{-1}. Major and rapid offshore deposition in the Atlantic immediately following sea floor spreading and then decreasing to low rates until the present (Rust and Summerfield, 1990)	125	Brown et al., 2000

TABLE 2(CONT.)

Name	Margin type (Margin stage)	Fission track and (U-Th)/He ages (My)	Comments and reference	Cosmogenic data (m My^{-1})	Comments and reference	Geophysical evidence	Geological evidence	Age (My)	Reference (structure and age)
South Africa									
	Shoulder (Passive)	N.D.		50-95 (escarpment retreat) 6 (upland surface)	Rock samples (Fleming et al., 1999)	N.D.	N.D.	130-150	Brown et al., 2000; Fleming et al., 1999
East Africa									
	Shoulder and Arch (Rift)	75-423	FT ages are older than rifting (van den Haute, 1984)	N.D.		N.D.	Normal faults within 3-5 km from base of escarpment	20	Ollier, 1991 (in Bloom 1998)
SE Australia									
	Arch (Passive)	Fission track ages: 230-360 upland 80-175 coast. (U-Th)/He ages: Coastal plain - 80 to 90 Ma. Upland plateau > 200 Ma.	(Moore et al., 1986; Dumitru et al., 1991). Persano et al., 2001	2 km/My	Rates of knick-point retreat in channels that cross the escarpment (Weissel and Seidl, 1998)	Gravimetric and magnetic anomalies parallel and below escarpment (Young, 1989; Webb et al., 1998)	Stationary drainage divide since at least the jurrasisc ((Nott and Horton, 2000). Geomorphologic evidence for Cenozoic low rates of erosin (van der Beek and Braun, 1999)	90-150	Ollier and Pain, 1994; Veevers et al., 1991

TABLE 2(CONT.)

Name	Margin type (Margin stage)	Fission track and (U-Th)/He ages (My)	Comments and reference	Cosmogenic data (m My^{-1})	Comments and reference	Geophysical evidence	Geological evidence	Age (My)	Reference (structure and age)
India									
	Shoulder (Passive)	165-226	Older than rifting or sea floor spreading Kalaswad, 1993	N.D.		Gravimetric and magnetic anomalies parallel and below escarpment (Kalaswad, 1993)	Lateritic soils on drainage divide indicating the stability of the drainage divide (Widdowson and Cox, 1996)	65	Kalaswad, 1993
Brazil									
	Shoulder (Passive)	60-100 (coast) 130->300 (upland)	Uniform FT ages on coastal plain (Gallagher et al., 1994)	N.D.		N.D.	N.D.	125	Brown et al., 2000
Baikal									
	Shoulder and arch (Rift)			N.D.		N.D.	N.D.	27	Logatchev and Zorin, 1992 Hutchinson et al., 1992

Note: N.D.= no data.

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