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Rifts of the world

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ABSTRACT

Rifts are fault-bounded elongate troughs, under or near which the entire thickness of the lithosphere has been reduced in extension during their formation. They form in most tectonic settings, including above mantle plumes, and at all stages of the Wilson Cycle of ocean opening and closing. The purpose of this paper is to present an updated inventory of the rifts of the world both in graphic and tabular form. We have identified 290 rifts in Eurasia, 101 in Africa (including Madagascar), 11 in Australia, 1 in New Zealand, 81 in North America, 68 in South America, and 16 in Antarctica. These numbers are clearly an underestimation, because of (1) the ones we missed and (2) the ones that were too small to be included here. The greatest majority of rifts formed through passive mechanisms, i.e., without active mantle participation. In the future, it would be more helpful to consider rifts in terms of taphrogens, i.e., regions of intense extension, in which many rifts and grabens occur as a result of general lithospheric stretching, to be able to understand the tectonic regimes that give rise to rifting.

INTRODUCTION

The purpose of this paper is to present an updated inventory of the rifts of the world. The endeavor follows intensive efforts in the early 1970s to map and classify (Milanovskii, 1972) and in the mid-1970s to map and list the rifts of the world (Burke et al., 1978); there were further iterations by Milanovskii (1980, 1983a, 1983b, 1987) plus another in only map form nearly a decade later (Şengör, 1995). Although our inventory is still considerably larger than any hitherto published, it should be considered to be of a preliminary nature, because of the difficulty of adequately surveying the vast literature on the topic of rifts and because of the accelerating development in rift studies worldwide. We would therefore appreciate any criticism and any additional rift to be placed on our list. We would particularly welcome copies of publications concerning rifts not present in our list.

In the future, a list of *taphrogens,* defined herein as lithosphere-scale structures that are commonly formed from a linked system of rifts and grabens that stretch the lithosphere, will undoubtedly prove much more informative than a list of individual rifts for illustrating extensional phenomena in Earth history. By analogy, we commonly display orogens when we wish to illustrate convergent phenomena in Earth history and not individual nappes or folds (e.g., Şengör, 1990a, 1991). To try to do the latter would be a well-nigh impossible task. A list of nappes would be time- and energy-consuming to generate and too extensive to permit recognition of any underlying pattern. Attempts of limited usefulness of that sort resulted in the many mute terrane lists and maps that were so fashionable not that long ago (e.g., Howell, 1985, 1989; Leitch and Scheibner, 1987; Dallmeyer, 1989; Wiley et al., 1990). They are gradually being abandoned, as the geological community rediscovers that genetic entities represented by orogens (Kober, 1921) and orogenic systems (Stille, 1928; Şengör, 1990a)—while having a large component of human guesswork involved—still are im-

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mensely more informative and easy to question in their simplicity, elegance, and daring than a list of numerous empirical fault-bounded packages making inquisitive checking impossibly difficult (cf. Şengör, 1990a, 1990b, 1993a; Şengör and Dewey, 1990; Şengör et al., 1993; Şengör and Natal'in, 1996a, 1996b; Hansen, 1999).

In the following paragraphs, we review the concepts of *graben, rift,* and *taphrogen* with a view both to showing the basis of our mapping—i.e., what we mapped and what we left out—and to pointing out what needs to be mapped in the future. Although we have considered a few taphrogens, the limited time at our disposal did not allow us to be systematic. We think that mapping taphrogens needs to be undertaken in a systematic way in the future, if we are to understand the properties and interrelations of extensional systems.

CONCEPTS OF GRABEN, RIFT, AND TAPHROGEN

Rifts are fault-bounded elongate troughs, under or near which the entire thickness of the lithosphere has been reduced in extension during their formation (cf. Şengör and Burke, 1978, p. 419; Şengör, 1995, p. 53). They form in most tectonic settings, as shown subsequently herein, and at *all* stages of the Wilson Cycle of ocean opening and closing (Burke, 1978). They form sedimentary basins that preserve a record of the tectonic environment in which they originate and/or evolve much better than orogenic belts, though the range of environments forming in them is much more limited and contains much less diverse fauna and flora. Igneous activity is a common accompaniment to rifting, but again displays a more restricted range of types than found in the orogens. Rift metamorphism is modest compared with that accompanying orogenic processes, the most extreme cases being known from the "metamorphic core complexes" of the southwestern United States (Armstrong, 1982) and elsewhere (e.g., Burchfiel et al., 1992; Davis et al., 1996).

Many rifts do not survive as rifts in the geologic record. Commonly, when the extension factor (β, defined as the extended width divided by unextended width: cf. McKenzie, 1978a) grows beyond 3 (cf. Le Pichon and Sibuet, 1981), seafloor spreading tears the continent asunder and destroys the rift. Remnants of rifts forming continental margins are later commonly incorporated into orogenic belts and become deformed and metamorphosed. Some rifts, however, do not generate oceans and end their tectonic life during the rift stage. These get incorporated into the cemetery of fossil structures of the Earth as rifts, comparable to an individual who dies at infancy. These have been inappropriately called "failed rifts" in the geological literature, because they "failed to generate an ocean." What are generally called "failed rifts" are, in reality, perfectly successful rifts, *as rifts,* but are "failed oceans" and that is why "failed rift" is an inappropriate appellation.

Rift and *graben* generally are used interchangeably in the geological literature. Şengör proposed (1995) to confine the term *graben* to those structures that *do not* penetrate the lithosphere (i.e., "thin-skinned grabens" of Voight, 1974) and apply the term *rift* to those that *do* (i.e., "thick-skinned grabens"; see Voight, 1974, especially footnote 12; by "structure penetration," we here understand *the penetration of the extensional strain,* which creates different structures at different structural levels). Voight's proposition is supported by the history of these two terms.

Graben is a German word meaning a ditch or trench. It entered the language of geology via mining. In the miners' jargon, "grabens . . . are depressions or troughs in horizontal beds, which are much longer than they are wide" (Jacobsson, 1781, cited in Rosenfeld and Schickor, 1969). The word was not used commonly, though, until Suess (1883, p. 166) used it for strips of country subsided between two normal faults. The way Suess used it, especially in relation to the East African rift valleys (Suess, 1891, 1909), *graben* is equivalent to *rift.*

For Suess's meaning of *graben,* Gregory (1894, p. 295) introduced the term "rift valley" from the root "reve" meaning to tear apart or to pull asunder. *Thus, whereas the word* graben *is purely descriptive,* rift *involves an interpretation, i.e., extensional rupturing of a formerly continuous medium.* As originally used by the miners, "grabens" implied smaller and shallower structures than what are called "rifts." This distinction lives on in the collective memory of European geologists, although it is seldom given expression. Zeman (1979, p. 58; also see the references cited therein) is one of the few who has emphasized that distinction in print: "Some use the term [rift] for all grabens . . . , others believe the rifts to be associated with abyssal changes in the crust. . . . The author of this paper gives preference to the latter. Hence the rifts are grabens restricted to a thinned crust, accompanied by volcanism and connected with the elevated upper mantle by means of deep-seated faults (deep-seated grabens sensu St'ovícková, 1973)."

Examples of *grabens* in our—and the traditional—sense are the landslide-related graben systems that formed during the 27 March 1964 Prince William Sound earthquake in Alaska (Wilson, 1967; Voight, 1974) and the grabens of the Canyonlands National Park in Utah, which resulted from disintegration of the sedimentary section above the Upper Carboniferous gypsum-bearing Paradox Formation owing to flow down a gentle dip (McGill and Stromquist, 1974). It would greatly help to avoid confusion if one adhered to the graben versus rift distinction in the study of extensional structures. *In our compilation, we list only rifts, as defined herein, except where stated otherwise.* (However, if the word *graben* is part of a well-known designation for a specific rift, we have retained it in our compilation).

Naturally, using *rift* for lithosphere-penetrating structures and *graben* for those that do not go through the lithosphere robs our terminology of a neutral term to designate normal-fault-bounded troughs regardless of how deep they penetrate. We suggest that geologists use the term *extensional fault trough* or *V-trough* for such structures. Extensional fault troughs could be grabens or could be rifts. Their compressional counterparts could be called *compressional fault troughs* or *A-troughs,* and strike-slip counterparts then would be *strike-slip fault troughs* or *I-troughs.* If one side of a fault trough is delimited by an extensional fault and the other is bounded by a compressional fault (as in the case of many foreland and hinterland flexural basins), or one side by a strike-slip fault and the other by a normal or a thrust fault (as in many flower structures), one could then speak of a *hybrid fault trough.* Hybrid troughs could in turn be compressional strike-slip (AI-troughs) or extensional strike-slip (VI-troughs) (Fig. 1).

Currently, no term is generally employed to designate *regions of intense extension,* in which many rifts and grabens occur as a result of general lithospheric stretching. For comparable *regions of intense shortening* the term *orogen* has been in common use since Kober's (1921, p. 21) suggestion. A corresponding term for zones of intense extension is clearly needed, and this need has been felt ever since the word *graben* began to be used in the meaning of what we call a rift. Eduard Suess, who was the first to appreciate the existence of large regions of extension on Earth, wrote, "The investigation of a single sunken area or of a single line of subsidence does not lead us far. So long as each fold in a mountain chain was considered separately and every anticlinal of the Jura mountains was regarded as though it were the result of an independent linear elevation, further insight into the nature of folding generally was impossible. Just as the folds of a great chain are arranged according to universal laws, and as each of these is dependent on the neighboring folds and on the general structure of the chain, so in large areas we see lines of subsidence arranged in nets or systems which, taken together, indicate the position of a field of subsidence, and, like the folds of a mountain chain, are the effects of a common cause." (Suess, 1883, p. 165; in the English edition: Suess, 1904, p. 125.) The need for a handy term for regions of extension has led some to use those terms invented for compressional regions with extensional adjectives, such as "graben tectogen" (Illies, 1974a, p. 6) and "extending orogen" (e.g., Wernicke, 1981, 1985). But such terms are likely to lead to confusion as they seem to suggest the extension of a preexisting compressional structure rather than the extensional structure itself.

Şengör (1995) suggested that geologists use the term *taphrogen,* derived from Krenkel's (1922, p. 181 and footnote) term *taphrogeny,* meaning trough-building (from the Greek ταφρος = ditch or trench), to designate the extensional counterparts of orogens.[1] Thus, *taphrogens are lithospheric-scale structures, commonly formed from a linked system of rifts and grabens that stretch the lithosphere.* Advanced taphrogeny eventually leads to ocean formation (which may be called *thalassogeny.* Kober, 1921, p. 48: from the Greek θαλασσα = sea). If taphrogeny stops before producing ocean (i.e., before leading to thalassogeny), it causes subsidence and creates large basins overlying taphrogens (cf. McKenzie, 1978a). In other words, intracontinental taphrogeny leads to *koilogeny* (Spizaharsky and Borovikov, 1966, p. 113 and following: from the Greek κοιλος = hollow).

Owing to the need to recognize not only individual extensional structures, but also *patterns of structures* (i.e., whole taphrogens), Şengör (1995) proposed a hierarchical classification of rifts in the framework of taphrogens, which goes from pure geometry to dynamics (Fig. 2). His classification was primarily designed to facilitate considering observations not only from individual rift fragments preserved in the geologic record, but also from parts of larger patterns of rift groups in relation to one another and/or to other structures such as koilogens, thalassogens, and orogens. Owing to its hierarchical nature, Şengör's classification also discloses the environment and path of formation of a given rift. When the editors of the present volume asked us to prepare a list of the rifts of the world, they requested that every rift be put into its appropriate slot according to Şengör's scheme. In this paper, rifts are thus classified by using Şengör's letter and number notation. In most cases, we confined ourselves to kinematic and geometric aspects of a given rift. This approach was partly owing to our ignorance of the dynamic aspects of most rifts and partly because once a kinematic-geometric line is established in Şengör's scheme, the dynamic class in the classification into which a rift would fall is generally obvious.

However, when rigorously pursued, Şengör's classification leads up to the dynamic categories d1 or d2, namely, active and passive rifts, respectively (Şengör and Burke, 1978). It can be used as a sort of checklist in searching for ancient plumes, for the d1 category contains exclusively plume-related rifts. The present compilation shows, however, that the geometric categories can be more varied than indicated in Şengör's original classification. This complication results from the structural and the thermal state of the lithosphere at the time of rifting. However, the next stage, the kinematic categories, leads more safely either to the d1 category or the d2 category. The classification is more genetic than descriptive. As Gould (1989, p. 98) wrote, "classifications are theories about the basis of natural order, not dull catalogues compiled only to avoid chaos." An allegedly "descriptive" classification commonly generates an artificial air of finality and tends to choke further questioning. A genetic classification, by contrast, is nothing more than a hypothesis in the Popperian sense, "a theory of causal ordering" (Gould, 1986, p. 63), and invites criticism and eventual refutation.

[1]Strictly speaking, only intracontinental orogens, collisional or otherwise. The following one-to-one comparison may make our meaning clear: (1) *Orogen:* intracontinental convergence; taphrogen: intracontinental extension. *Orogen:* continental collision; *taphrogen:* continental separation. *Orogen:* crustal thickening; *taphrogen:* crustal thinning. *Orogen:* intercontinental convergence (i.e., subduction); *taphrogen:* has no corresponding act. *Orogen:* point collision with subduction continuing on both sides of collided point; *taphrogen:* beginning extension at a point with no action on any side of that point.

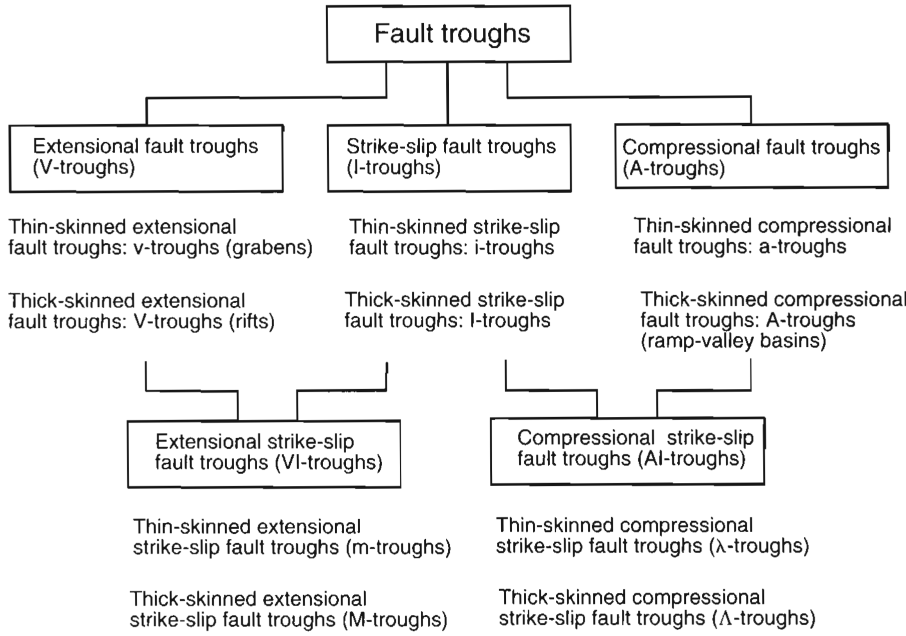

Figure 1. Terminology offered for discussion of fault-bounded troughs. The offered letter-based terminology has a mnemonic base, derived from the cross-sectional aspects of the troughs. Extensional fault troughs commonly have V-shaped cross-sections, bounded by one or two normal faults dipping basinward. Strike-slip troughs ideally generate basins with parallel, vertical sides. These could have been called H or I troughs. We chose I, because it more readily calls to mind the cross-sectional aspect of a strike-slip fault. Compressional troughs are bounded by thrusts verging towards the basin, calling to mind the shape of an A or a Λ. We chose A, to reserve λ for strike-slip/compression hybrids, as the lower case lambda has an upside-down v and a steep tail resembling a strike-slip fault cross-section. The scheme is self-explanatory and, if used in geological descriptions, may avoid much ambiguity or unnecessary verbosity. We have not used it in our Table 1, for it would have further complicated an already fairly complex listing. It is here offered for discussion. If it finds favour in the geological community, we hope to use it (or a revised form of it) in a comprehensive discussion of the world's taphrogens in a future paper.

ŞENGÖR'S CLASSIFICATION: A RESTATEMENT

The classification of rifts that Şengör (1995) proposed also embraces *groups of rifts,* i.e., taphrogens. It has three different categories that do not completely overlap, namely *geometric, kinematic,* and *dynamic.* In the following, the three different categories are identified with their initials, i.e., *g, k,* and *d,* respectively.

Geometric classification of rifts (see Fig. 2)

Rifts display five kinds of patterns of occurrence in map view (Şengör, 1983, 1995). From simplest to more complex, these are as follows:

(g1) Solitary rifts. *Solitary rifts* form small, fairly insignificant and very rare taphrogens and are extremely difficult to ascertain in the geologic record, because it is commonly hard to tell whether a given rift fragment is isolated or part of a larger taphrogen.

(g2) Rift stars. *Rift stars* (Cloos, 1939, p. 512) form when more than two rifts radiate away from a common center, building a fairly equant taphrogen. Rift stars are very common features of the structural repertoire of our planet today (cf. Burke and Dewey, 1973).

(g3) Rift chains. When several rifts are aligned end-to-end along linear or arcuate belts of rifting, they form *rift chains.* The East African rift system constitutes the best known active rift chain in the world.

(g4) Rift clusters. When several subparallel rifts occur in roughly equant areas, they are said to form a *rift cluster* (Şengör and Burke, 1978, p. 419). The two best-known active rift clusters in the world are the Basin and Range extensional area in North America and the Aegean Sea and the surrounding regions. The West Siberian taphrogen constitutes an inactive example of a rift cluster.

(g5) Rift nets. First recognized and named by Eduard Suess (1883, p. 165), *rift nets* constitute a rare pattern, which comes about when rifts form a roughly checkered pattern as in the Proterozoic basement of the East European platform or in the late Mesozoic in central north Africa. They resemble chocolate-bar boudinage and may have a similar origin, but more commonly, rift nets form in complex and rapidly shifting stress environments in which dominant extension directions change fast. Many rift nets in fact may represent two superimposed rift clusters.

Kinematic classification of rifts (see Fig. 2)

As rifts occur during all stages of the Wilson Cycle, the kinematic characteristics of the plate boundaries has been taken as a basis for classifying them according to the environment of the overall displacement and strain in which they form. There

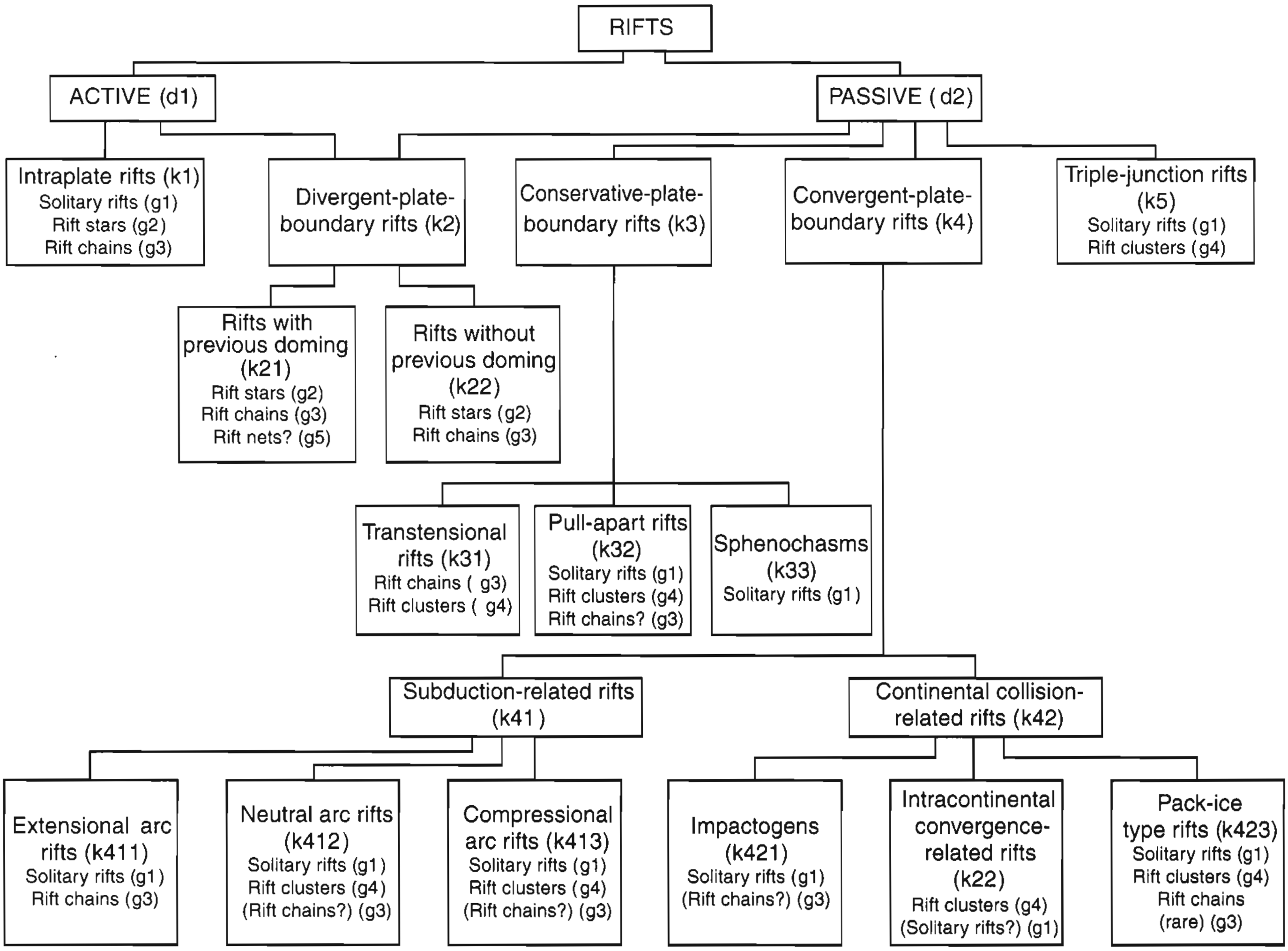

Figure 2. Classification of rifts (Şengör, 1995).

are three types of plate boundaries plus the plate interiors, with which four types of rift families correspond. In addition, problems of compatibility arise around some unstable triple junctions, commonly owing to involvement of hard-to-subduct buoyant lithosphere. Some of these problems lead to complex rifting that should be treated separately from the other four classes, thus creating a fifth kinematic class, herein called triple-junction rifts.

(k1) Intraplate rifts. Rifts surrounded entirely by undeformed lithosphere occupy this category. Such rifts are usually solitary, very small and very rare, and are difficult to detect in the geologic history. Some active examples are found in the northeastern United States in the Lake George and Lake Champlain rift structures (Burke, 1977).

(k2) Rifts associated with divergent plate boundaries. These rifts form as a direct consequence of plate separation along nascent divergent boundaries. All rifts along the East African rift system belong to this category. This category of rifts may be further subdivided into two classes as follows:

(k21) Rifts that form following an episode of doming. The divergent boundary along which rifts form is in this case preceded by an episode of lithospheric doming. The East African rift valleys are the most outstanding extant examples of such a situation (Burke, 1996). Rifts of Mesozoic age on the Atlantic margins of the Iberian Peninsula yield evidence for a comparable situation (Wilson, 1975).

(k22) Rifts that form with no prerift doming. In this case, rifts form without a prelude of uplift, as is the case in the Salton Trough in southern California. A good fossil example is the rifting of the Alpine Neotethys in the earlier Mesozoic (Stampfli and Marthaler, 1990).

(k3) Rifts that form in association with conservative plate boundaries. Conservative boundaries are, by definition, those along which neither extension nor shortening takes place. However, various reasons conspire to induce both extension and shortening to occur along considerable stretches of these boundaries (Christie-Blick and Biddle, 1985; Sylvester, 1988).

Rifts along conservative plate boundaries form in three different settings:

(k31) Transtensional conservative boundaries. If a conservative boundary is leaking because of a component of extension, it is called transtensional (Harland, 1971, p. 30 and especially Fig. 2). Many active rifts have a transtensional component, and fossil examples of such rifts may be recognized largely through the structures they contain or from their former bounding transform fault endings.

(k32) Pull-apart basins along conservative boundaries. Major strike-slip faults, the main structural expression of conservative plate boundaries, commonly have bends along them that either facilitate ("releasing bends": Crowell, 1974, Fig. 3) or obstruct ("restraining bends": Crowell, 1974, Fig. 3) movement along the strike of the fault. These bends may be primary, related to the initial nucleation of the fault, or secondary, formed through structural modifications imposed on a preexisting fault and/or system of faults. In both cases, extensional basins form along the releasing bends, in which the magnitude of extension equals the magnitude of cumulative strike-slip offset along the strike-slip fault since the formation of the releasing bend. Such basins are called "pull-apart basins" after Burchfiel and Stewart's (1966) apposite appellation, but the concept is much older. Crowell's (1974) fault-wedge basins are nothing more than special cases of pull-apart basins. Pull-apart basins come in all forms and shapes, notwithstanding the claim by Aydm and Nur (1982) that they display a constant aspect ratio at all scales.

(k33) Sphenochasms. Not all basins created by secondary extension associated with strike-slip faults are pull-apart basins. Some represent tears caused by either an asperity or differential drag along the strike-slip fault in one of the fault walls, in which the amount of extension changes from a maximum along the fault to zero at the pole of opening of the tear basin. Carey (1958, p. 193) called such wedge-shaped rifts that open toward a major strike-slip fault *sphenochasms* (from the Greek σφεν = corner, and χαω = to yawn).

(k4) Rifts that form in association with convergent-plate boundaries. A large family of rifts forms in association with convergent-plate boundaries. In this group, a first-order subdivision is between rifts associated with subduction zones and rifts associated with continental collision, although this scheme may artificially split some genetic groups, such as those rifts that presumably form owing to tension generated by excessive crustal thickening.[2] The usefulness of the present grouping is that it enables a rapid overview of the currently active rift environments and comparison with past ones.

(k41) Rifts associated with subduction zones. Three separate environments of rifting associated with subduction zones correspond with three different types of arc behavior, namely, extensional, neutral, and compressional arcs (Dewey, 1980; Şengör, 1990a).[3] In these environments, an enormous variety of rifts forms, and many evolve into oceans. In the following discussion, we consider only those that fail to generate oceans and get preserved as fossil rifts.

(k411) Rifts associated with extensional arcs. Once an arc begins extending, it generally splits along the magmatic axis (if such an axis is already in existence) and forms a small rift chain. Such a situation is today known from both the Okinawa rift and the Izu-Bonin arc system, where marginal basins are in the process of rifting. Such rifts generally do not get preserved intact in the geologic record, both because of the vicissitudes of the tectonic evolution of arcs involving common changes of behavior and because of later collisions with other arcs or continents. Preservation of rifts associated with extensional arcs in an uncompressed state takes place commonly when the associated arc switches from extensional behavior to neutral behavior.

In extensional arcs, rifts also develop orthogonal to the arc trend owing to the extension of the arc as it bows out in front of an expanding marginal basin (as, for instance, in Crete). This is similar to Carey's (1958) oroclinotath formation.

(k412) Rifts associated with neutral arcs. Neutral arcs are defined to have neither shortening nor extension across them. Therefore the only rifts that form in neutral arcs are those associated with arc-parallel strike-slip faults, which may be classified in the same way as the rifts that form along conservative plate boundaries. More complex rift basins may originate along such arc-parallel strike-slip faults, if the sliver in the forearc area (Jarrard, 1986, p. 235; "forearc plate" of Woodcock, 1986) disintegrates and its various pieces rotate about vertical axes.

Pull-apart basins in arcs are difficult to recognize. None of the major active strike-slip faults located in arcs has well-developed pull-apart basins along them (e.g., the Median Tectonic Line in Japan, the Atacama fault in the Andes, or the Philippine fault in the Philippine Archipelago), except the Andaman Basin that connects the right-lateral Sagaing and the Sumatra faults and that is likely floored by oceanic crust (cf. Hamilton, 1979). Also, the Sumatra fault may now be developing a pull-apart basin between 0 and 1 °N (Sich and Natawidjaja, 2000). Fossil and relatively undeformed examples of such basins have been inferred and mapped, however (e.g., the Chuckanut, Puget, and the Swauk basins in the state of Washington, in the northwestern United States: Johnson, 1985).

Sphenochasms along strike-slip faults in arcs are rarer still. Davis et al. (1978) have discussed two possible examples, the more recent of which may have created the "Columbia Embay-

[2]We emphasize that we are very sceptical about "extensional orogenic collapse" under the weight of uplands alone. Everywhere it has occurred, an additional process, such as tectonic escape, seems to have aided it. Moreover, in many places where it is proposed to occur, the number of structures responsible for extension and the actual amount of stretching are far smaller than proposed (e.g., the Alps), and the direction of stretching is at variance with the solely gravity-driven extensional orogenic collapse model (e.g., the Betic Cordillera). Where it has indeed occurred, it was aided by lubricating the collapse faults by granite injection as in the Himalaya (e.g., Burchfiel et al., 1992).

[3]Jarrard's (1986) seven or even five different types of arc behavior are far too detailed to be applicable to a general survey of the historical geology of arcs and are therefore not used here. For a discussion, see Şengör (1990a, p. 66).

ment" by motion along the Straight Creek fault in the latest Cretaceous and the earliest Cenozoic.

(k413) Rifts associated with compressional arcs. In compressional arcs, crust commonly thickens and lithosphere thins, both by heating and by eventual delamination. The arc becomes shortened across, and elongated along, its trend. This elongation commonly generates rifts at high angles to the trend of the arc.

(k42) Rifts associated with zones of continental collision. Three different environments of rifting form associated with the collision of continents: (1) *lines of extension* that radiate from points at which collision commences; (2) *regions of extension* abutting against sutures, and (3) *nodes of extension* in areas of complex deformation in forelands and hinterlands shattered by collisions. Impactogens (k421), rifts forming in intracontinental convergence belts (k422), and pack-ice-type rifts (k423) correspond with these three environments, respectively.

(k421) Impactogens. Impactogens are rifts that originate as a result of tensional stresses set up in a continent when it is hit by a pointed promontory of another continent. The best example today is the Upper Rhine graben between Germany and France, which formed in the middle Eocene upon collision in the Alps. Impactogens are commonly solitary rifts, but several impactogens may form along a long front of collision, if more than one promontory collides with the opposing continent (e.g., the Oslo-Skagerrak rift and the Viking-Central rift in the North Sea along the Variscan collision front in northern Europe).

(k422) Rifts forming along intracontinental convergence belts. These rifts are similar in principle to those described under k413 (rifts associated with compressional arcs) and indicate the elongation of the orogen along its trend during postcollisional convergence. The north-trending grabens in southern and central Tibet, which formed as a consequence of the shortening and east-west elongation of the Tibetan high plateau following collision along the Indus-Yarlung suture represent the best active examples of these.

(k423) Pack-ice-type rift basins. When a continental collision generates first impactogens and then rifts related to ongoing intracontinental convergence, along with conjugate strike-slip faults that help the sideways elongation of the shortening region along the orogen, the whole deformed area becomes divided into rigid and semirigid blocks, in central Europe termed *Schollen* (see Dewey and Şengör, 1979, footnote 1), that move with respect to one another along compressional, extensional, and strike-slip boundaries similar to drifting pack ice. In such a setting, rifts and grabens form in diverse shapes and orientations, as best exemplified today by the *Schollen*-regime of central Europe (Şengör, 1995, esp. Fig. 2.10).

(k5) Triple-junction rifts. Triple-junction rifts form at or near unstable triple junctions, at which plate evolution dictates the generation of "holes" owing to failure to create subduction zones along a plate boundary, commonly because one or more plates meeting at the triple junction consist of buoyant lithosphere.

Dynamic (genetic) classification of rifts (see Fig. 2)

Rifts also may be classified according to the origin of forces that lead to rifting. Şengör and Burke (1978) proposed that stresses that cause rifting may be imposed on the lithosphere directly by the mantle beneath it or they may result from two-dimensional plate evolution. Accordingly, they termed these two modes of rifting *active* and *passive.* The proposal to call passive rifting "closed-system rifting" and active rifting "open-system rifting" by Gans (1987) is misleading, because it is not necessarily obvious with respect to which parameter the system is considered open or closed (crustal addition, geochemical reservoir tapped, plate-boundary network, or original sedimentary provenance). Consequently we avoid it here.

(d1) Active rifting. "Active rifting" is rifting caused by mantle upwelling associated with hotspots in the mantle (see Şengör, this volume). In such environments, rifting was originally thought to result from the tension created by the extrados stretching (i.e. stretching occurring along the outer arc of a concentric fold; in other words on the extensional side of the neutral surface) caused by doming (Cloos, 1939). Studies since Cloos (1939) have shown that although doming in some instances may be sufficient to *initiate normal faulting,* it is not sufficient to *maintain rifting* and to create anything like our present rift valleys in Africa or the Rhine graben.

Two views have been advanced to explain the origin of the extension not related to extrados extension of domes rising above hotspot jets. One ascribes the rifting to basal shear stresses induced by a spreading plume head beneath a dome. The other holds the potential energy of the rising dome responsible for driving the rifting (see Şengör, this volume). All of these factors probably do contribute to maintaining the active rifting process at its habitually slow pace of considerably less than 1 cm/yr.

(d2) Passive rifting. Passive rifting refers to a mode of rifting in which the mantle under the rifting area plays only a passive role. In the passive-rifting mode, extension is caused by the two-dimensional motions of the lithospheric plates. In this mode of rifting, there is no prerifting doming related to a hotspot (Şengör and Burke, 1978). Kinematic mechanisms previously reviewed under the headings k22, k31, k32, k33, k411, k412, k413, k421, k422, k423, and k5 all may form rifts in a "passive-rifting mode."

There is only one kind of rift this classification does not consider: rifts that form by propagating from an already existing rift. Because propagation may take many forms, we thought it might be sufficient to indicate such rifts with the notation d2 to indicate their passive mode of opening. Figure 2 can be used as a "flow chart" to follow the evolutionary histories of the various kinds of rift basins reviewed in the following sections.

The two dynamic categories of Şengör's (1995) classification have the property of assigning rifts into two main classes that may also be named *plume related* and *plate-boundary related.* So far as we know, mantle dynamics directly interferes

Figure 3 (this and following page). Rifts of the world, excluding Antarctica. Rifts of Antarctica are shown in Figure 6. Numbers refer to Table 1.

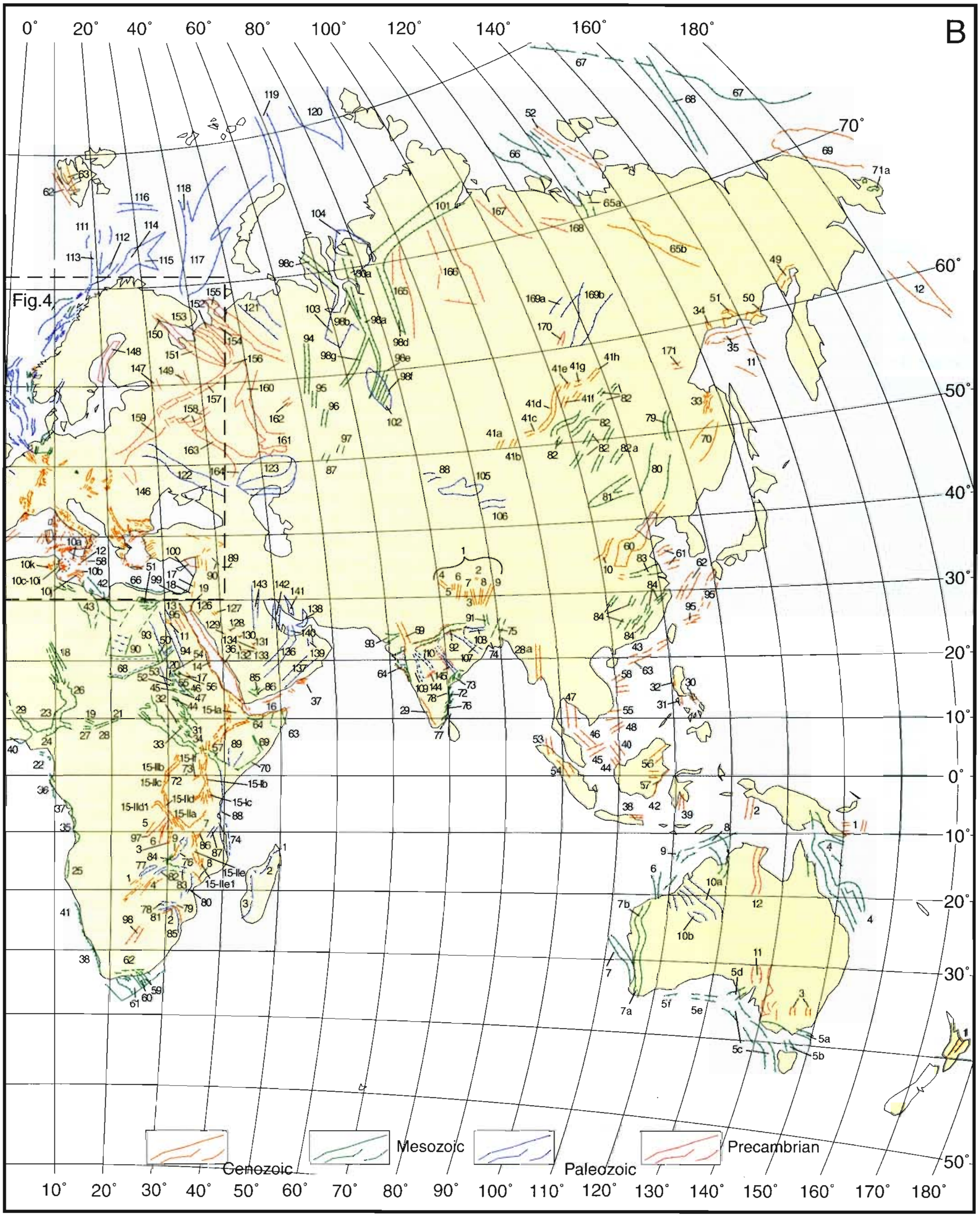

Figure 3 (*continued*).

with the behavior of the lithosphere via convection. This convection seems multiscaled and both maintains the plate motions and generates plumes originating at various depths and having different degrees of vigor (see Burke, 1996; Csrepes and Yuen, 2000). All intraplate tectonism—so far as it is not related to loads put on top of the lithosphere and so far as it is not related to bending the lithosphere near plate boundaries or unrelated to sinking heavy objects along old subduction or collision zones—appears related to the activity of the plumes. Another class of purported source of intraplate deformation is membrane stresses that allegedly result either from the wandering of plates on a nonspherical Earth (Turcotte and Oxburgh, 1973; Turcotte, 1974) or from the secular thermal shrinking of the planet (Solomon, 1987). It is unlikely that in the time scales involved in moving the plates a quarter of the way around the Earth or in cooling the Earth sufficiently to create serious mismatch between lithospheric curvature and its support, stresses can be created that give rise to fractures penetrating the lithosphere (cf. Burke and Dewey, 1974; Burke et al., 1981, p. 828–829).

For these reasons, *all hotspots must be related only to mantle plumes,* although the term *hotspot* itself has no genetic connotations whatever and simply means "intraplate magmatism." Kevin Burke (2000, written communication) has insisted on this nongenetic aspect of the term and has suggested that hotspots may result from magmatic activity associated with (1) rifts, (2a) shallow plumes of the kind that probably gave rise to the swell-and-basin topography of Africa, (2b) deep plumes of the kind that has created the Afar triple junction (see Burke, 1996), and (3) an uncertain origin. Despite that, every time Burke had occasion to discuss the origin of hotspots, he has only referred to the activity of the mantle, specifically to plumes (e.g., Burke and Wilson, 1976; Burke and Kidd, 1980; Burke et al., 1981; Burke, 1996). This is in agreement with Şengör's result (this volume) that if a rift is not related to the activity of a plume, it must then be related to the activity of a plate boundary or a plate-boundary zone. That is why one can think of those rifts that form by active-mantle processes as plume-related rifts and those in whose formation mantle dynamics plays no direct role as plate-boundary rifts (see Şengör and Burke, 1978; because, with the exception of sporadic impact-related magmatism, we are unaware of any significant magmatism on Earth that is definitely related neither to plumes, nor to plate boundaries, nor to plate-boundary zones, Burke's third category i.e., those rifts whose origin is uncertain, we leave out of discussion now).

PRINCIPLES UNDER WHICH THE PRESENT LIST WAS COMPILED

An inventory of the rifts of the world is presented in graphic form in Figures 3–6 and in tabular form in Table 1. Table 1 lists only true rifts (as defined by Şengör) and omits grabens as already defined (though if "graben" is a part of the name of a rift, we retain it) and what is listed is shown in Figures 3–6. We incorporated into our list only those rifts that are still recognizable as rifts. These exclude backarc basins but include some gently compressed rifts, and "gentle compression" in some cases may involve a total of 10 km shortening as in the case of the Benue rift. The criterion is that the structural inferiority of the rift basement with respect to its shoulders should not be inverted by the subsequent shortening. The reader will find inconsistencies in our usage commonly introduced by force of habit—if we have been used to calling something a rift, we are likely to have included it, such as the Soria basin in Spain—notwithstanding the thrusts it has—and the Benue—although it may even have had subduction! We think that the number of such examples is so small as not to destroy the uniformity of the characteristics common to the rifts we list in Table 1. Here again we invite criticism to improve Table 1.

We have indicated a few taphrogens—those the reader will recognize without much difficulty. But Table 1 should by no means be considered to include an exhaustive list of taphrogens. Quite the contrary: it includes only a few. The identification of the rifts in taphrogens also reflects the experimental nature of the exercise: In east Africa, we denoted the two major subtaphrogens by Roman numerals, in the Basin and Range we did not, because the further division into rifts was not indicated.

Figures 3–6 are only a guide to the whereabouts of the rifts listed in Table 1 and show their shapes only roughly. They are not meant to be tectonic maps of rifts. They are only index maps and are not reliable for a statistical analysis of rift trends. If used for such a purpose, they would give a rough idea globally, but in many regions might mislead the statistician.

Both in Table 1 and Figures 3–6, *age of a rift* means age of first rifting. This is commonly the age of main rifting, but in some regions, this is not so, for example in some rifts in northwestern Europe. For most rifts, we have not listed episodes of subsequent rifting, but in this approach again we have not been consistent. The reader will find a number of episodes of rifting listed for some entries. Similarly, for some entries, additional information is supplied in footnotes. We have done this where we encountered problems in establishing some aspect of the rift under consideration or when we felt compelled to deviate from some common usage or practice, or where we felt additional information was necessary for the justification of our assignment of it to one of Şengör's (1995) classes. Also, for a few rifts, our sources disclosed no names, and we had to invent names for them; how we did this is always explained in a footnote. Because taphrogens were not recognized before, we had to invent names for them too. We adhered to the tradition of using the names of ancient peoples and places derive the names. The source and compass of these names are also given in footnotes.

References are given to enable the reader to locate the rift, to get an idea of its shape and age, and to be led to further sources. For most rifts, more than one reference is provided. For some, we had to make do with a single reference. Generally, the single references we chose contain abundant information. In some instances, we cite numerous references for two prin-

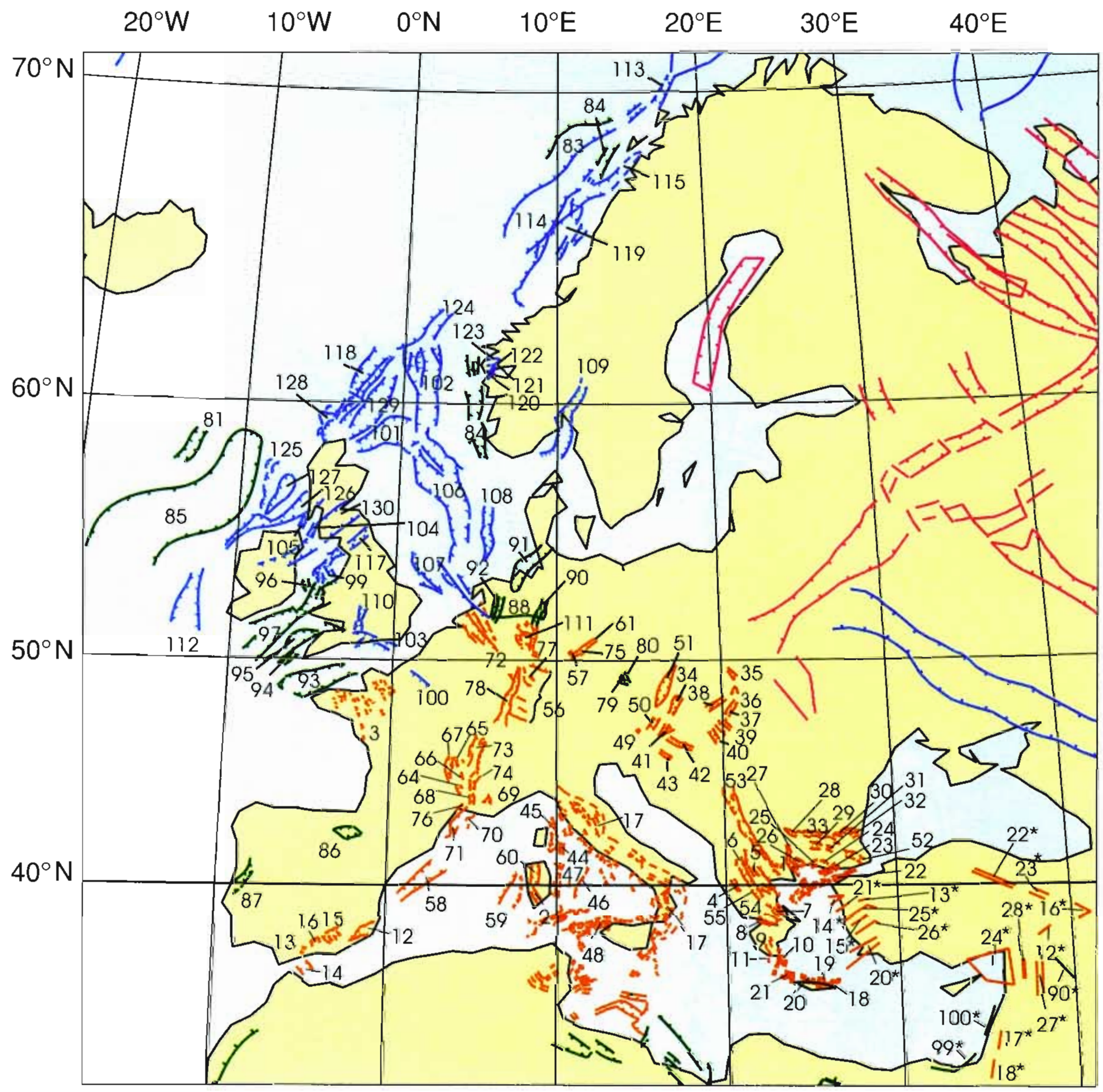

Figure 4. Rifts of western Europe and Turkey (for global context, see Fig. 3). The Hammersfest and Bjørnø rifts are off this map along the northern edge (they appear in Fig. 3). The details of the Turkish rifts appear in the Asian part of Table 11. Numbers refer to Table 1 entries.

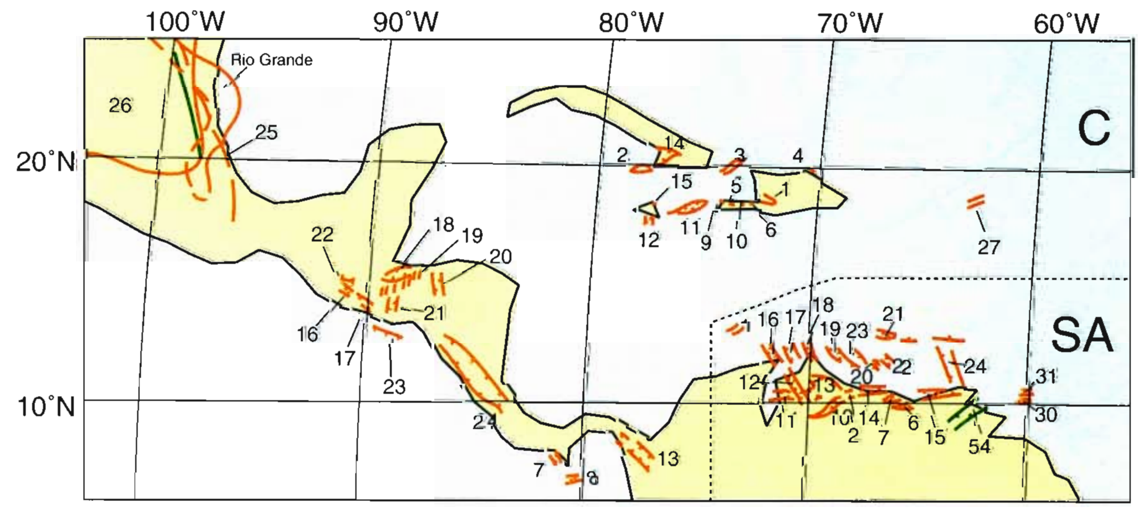

Figure 5. Rifts of the Caribbean and Central America (for global context, see Fig. 3). Part of diagram identified as SA contains rifts whose details appear in the South American part of Table 1, and the part identified as C contains rifts from the Caribbean and Central America list of Table 1. Numbers refer to Table 1.

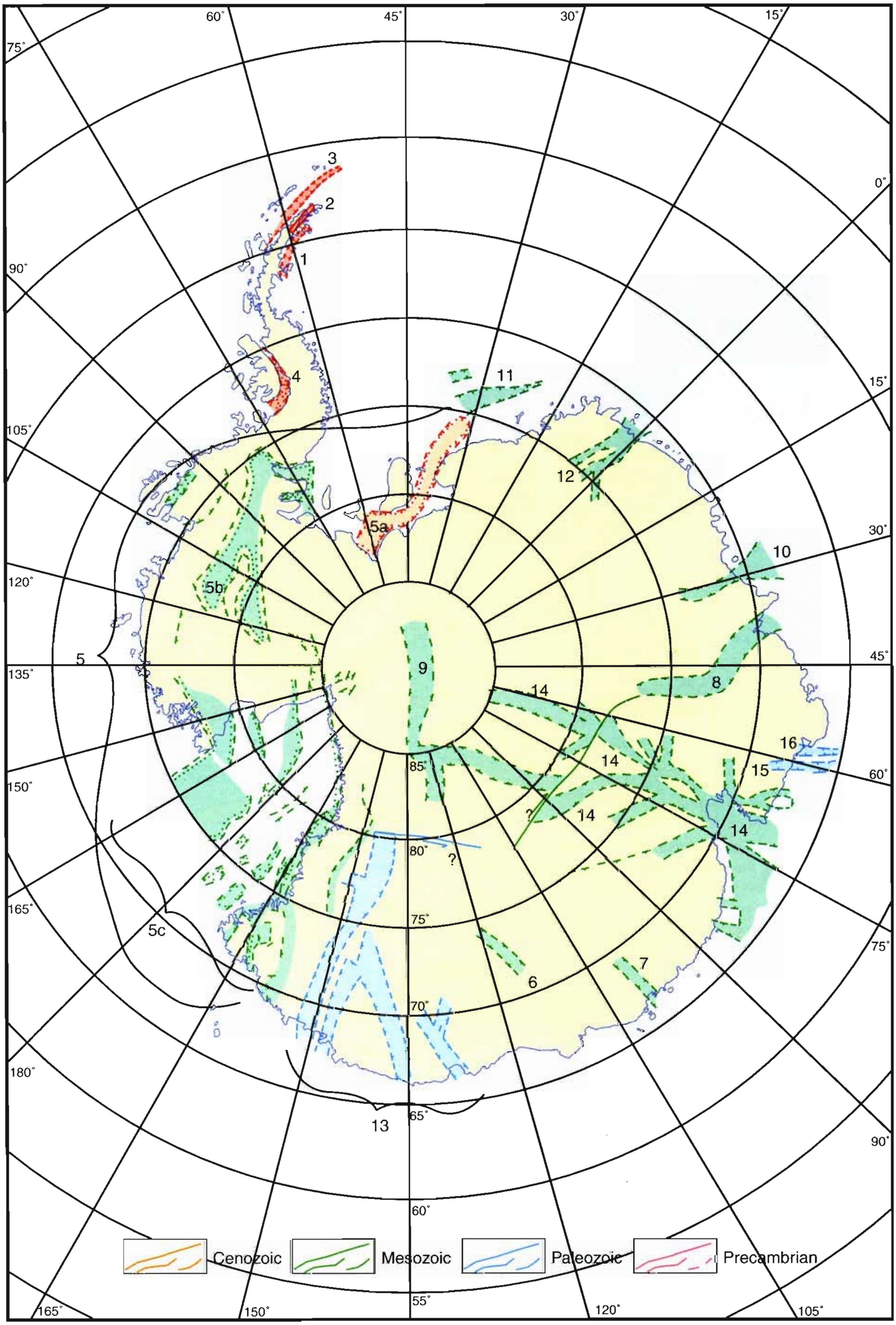

Figure 6. Rifts of Antarctica. Numbers refer to Table 1. A number of rifts along Antarctic continental margins known from cross-sectional data only are not shown.

cipal reasons: Either the feature under consideration has not been described completely in a few sources, or it is so large as to preclude having a few comprehensive sources devoted to it solely. Some of the taphrogens we list fall under the latter category.

The place of a rift in Şengör's (1995) classification is not infrequently our guess on the basis of a quick review of the principal traits of its geologic history. Some have been assigned slots by association, and others, by tectonic position. Naturally, only those rifts we are closely familiar with could be classified with some measure of confidence. The reader should view the assigned classes mostly as educated guesses based on flimsy data provided to form a starting point for a fruitful discussion.

As we have emphasized herein, this is a preliminary list, originated in haste. We hope to improve it and make it eventually a basis for mapping taphrogens on the face of the Earth. We would therefore be grateful for any criticism and additional pieces of information.

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(*References begin on page 456*)