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Life span and fate of basins

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ABSTRACT

The life span of each main class of sedimentary basin is estimated from published data. Life spans vary over at least three orders of magnitude, from <1 m.y. for trench basins to >100 m.y. for passive-margin and intracratonic basins. The life-span estimates are used to calibrate a chart of basin groups that focuses on the likely basin fates; i.e., depositional, deformational, or thermal. Consequent fates, predetermined by the tectonic setting of a particular basin class, are distinguished from contingent fates, which are independent of basin type. Accretion of trench-basin fill is, for example, a consequent fate, whereas inversion (far-field shortening) of a rift basin is a contingent fate. Life-span data are also used to calibrate the Wilson Cycle and indicate that it has an average duration of ~260 m.y. This is certainly an underestimate, because basin life spans are an imperfect proxy for the duration of subduction and collision zones.

Keywords: sedimentary basins, Wilson Cycle, convergent, divergent, strike slip, intraplate.

INTRODUCTION

The variety and diversity of sedimentary basins present an ongoing challenge of basin classification (e.g., Miall, 1990; Busby and Ingersoll, 1995; Einsele, 2000). This challenge is more than one of neat organization. An understanding of basin types and their relationships is important for diagnosing basin mechanics and for assessing the economic potential of basins for hydrocarbons and mineralization.

Criteria used to classify sedimentary basins include their geometry, the nature of their fill, the type of underlying crust, the position relative to plate boundaries, the kinematic nature of such boundaries, and the basin-forming mechanism. An undervalued basin characteristic is its life span, the time between its birth and death (Ingersoll and Busby, 1995). Basin life spans vary by at least three orders of magnitude, emphasizing that not all basin classes are of equal significance. Assessing the life span of basins also focuses attention on the typical fate of each class of basin. Some evolve into another basin type, some decay thermally, and some are deformed and uplifted, inevitably or not. A calibrated graphical display of these basin fates is presented for discussion. Finally, the data on basin life spans are used to measure a typical Wilson Cycle, the simplified but enduring model of how the tectonic settings of basins evolve through time.

BASIN CLASSES

The basin classification used in this paper (Fig. 1) derives from that of Dickinson (1974) in being based on plate-tectonic setting. Dickinson's classification underpins many current schemes (e.g., Miall, 1990; Busby and Ingersoll, 1995), and matches well with schemes based on other criteria, such as the nature of the underlying crust (e.g., Kingston et al., 1983; Einsele, 2000). The classes chosen here are those in common use and those for which data can readily be extracted from the literature.

The classification (Fig. 1) is designed to capture the main basin types, rather than being fully comprehensive. Some types may seem to have been omitted: in most cases, these have been combined with analogous basins. So, rift basins here include proto-oceanic rifts and the rift phases of aulacogens and impactogens. Passive margins also include sectors with major prograding deltas, sometimes distinguished as continental embankments (Ingersoll, 1988). Ocean basins are taken to include their constituent ocean islands, plateaus, and aseismic ridges. Active and remnant ocean basins are not separated, although it is recognized that a remnant ocean basin brought close to a continental margin by subduction may host distinctive sediment thicknesses (Graham et al., 1975). Foreland basins are taken to include any piggyback or wedge-top basins that form on the generating thrust belt (DeCelles and Giles, 1996). Continental platforms are regarded as the depositional feather edge of the adjacent basin—typically continental margin or foreland—rather than a separate basin class. Successor basins (e.g., Graham et al., 1993) are omitted because of their likely diverse origins and the limited database.

Strike-slip basins present a challenge in all classifications and are often split into several classes (Miall, 1990; Nilsen and Sylvester, 1995). Here (Fig. 1) they are grouped together, a simplification justified by their generally small size and short life span. They are seen here mostly as localized basins along faults onto which the oblique components at plate boundaries are partitioned. This view is not meant to underrate the importance of strike-slip deformation—most plate bound-

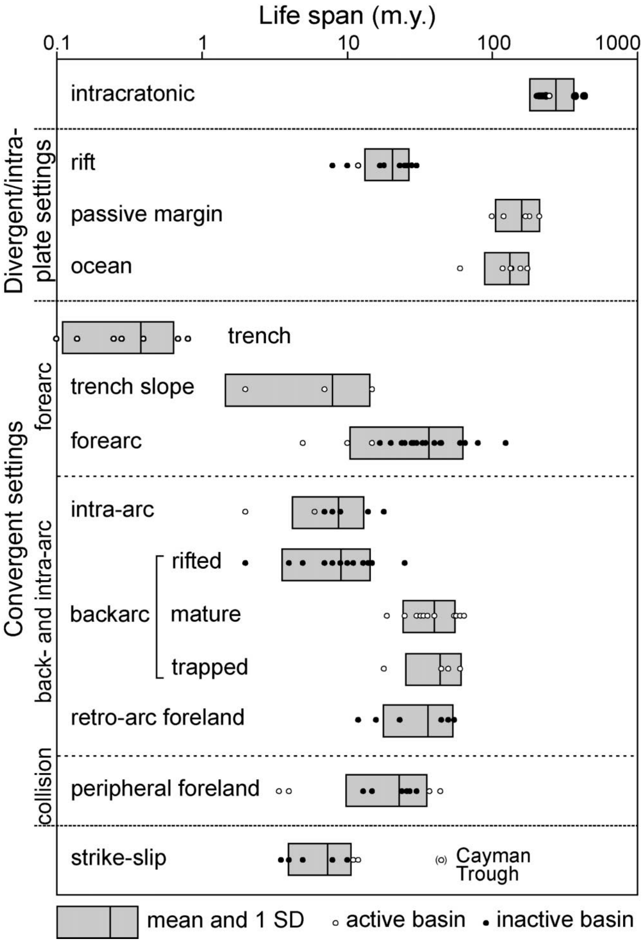

Figure 1. Life span of different classes of sedimentary basin on logarithmic age scale. Data (points) mainly from compilations by Einsele (2000) and Busby and Ingersoll (1995), with additional data from Glennie and Underhill (1997) (intracontinental and rift basins); Scotese et al. (1988) (ocean basins); Leggett (1982) (trench and trench-slope basins); Tamaki and Honza (1991) (backarc basins); and Allen and Homewood (1986) and Kneller (1991) (foreland basins). SD is standard deviation.

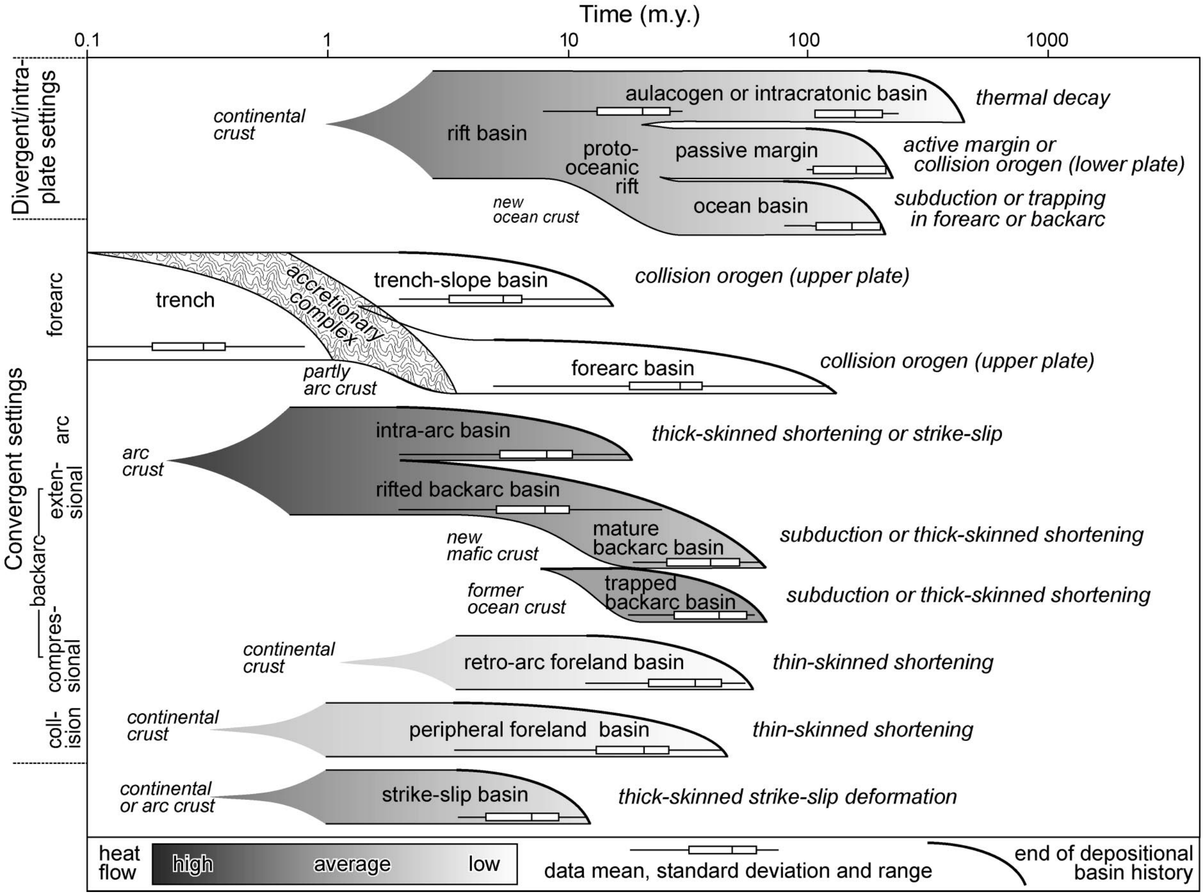

Figure 2. Typical fates of different classes of sedimentary basin through time, plotted on logarithmic scale. Small italics show basement to each class. Large italics show deformational or thermal consequent fates of each class. Estimates of basin heat flow are from compilation by Allen and Allen (1990).

aries (60%, according to Woodcock, 1986) have a significant oblique component—but rather to recognize the low basin-forming potential of a strike-slip system compared with a reverse- or normal-fault system.

Backarc basins are the only class to be subdivided here more than is usual (Fig. 1). In the context of basin life span, it is useful to separate out the backarc rift phase from the overall age of a spreading basin and to distinguish those backarc basins formed by trapping sectors of ocean crust behind a new subduction zone.

BASIN LIFE SPAN

Method

Life-span data from 137 basins are plotted in Figure 1, together with the mean and standard deviation of each basin class. The main data sources are given in the caption; most references are to compilations in which the primary sources are cited (see Data Repository[1]). Note the logarithmic life-span scale and its range over four orders of magnitude. This range suggests that the more conspicuous life-span contrasts between basin classes are robust, despite small sample sizes and uncertainties in life-span estimates for each basin.

Some further limitations of the parent data set should be noted. First, the life span of a trench is taken to be that of each packet of trench fill, terminated by subduction erosion or by accretion into a subduction complex, rather than that of the topographic trench. An analogous, though less marked, effect arises with foreland basins.

Second, data from active and inactive basins have been combined in each basin class. Active basins, with their unfulfilled life span, might be expected to lower the mean of a class. Inspection of the raw data (Fig. 1) suggests that this is not a consistent effect; the longest-lived strike-slip and peripheral foreland basins are still active. Removal of data for recent basins is not a practical option; almost half the basin classes are entirely dependent on such data for reliable life-span estimates.

A third limitation concerns the smallest life-span value in a class: should not most basin classes show a low-life-span tail reaching toward zero? In practice, each basin type has a lower threshold life span when it has acquired a significant thickness of fill, or, for recent basins, a marked topographic expression: e.g., ~1 m.y. for an intra-arc basin or ~10 m.y. for a retro-arc basin. This threshold is of little theoretical significance and, because of the logarithmic scale, has little effect on the mean life span in any basin class.

Results

Four scales of basin life span are evident (Fig. 1), more qualitatively recognized by Ingersoll and Busby (1995). Trench basins have a very short life, typically between 0.1 and 0.6 m.y. (range 0.1–0.8 m.y.). Trench-slope, intra-arc, rifted-backarc, and strike-slip basins also have short lives, mostly between 3 and 15 m.y. (range 2–25 m.y.). More long-lived basins, typically >10–70 m.y. (range 4–125 m.y.) are rift, forearc, backarc, and foreland. Intracratonic, passive-margin, and ocean basins have very long lives, mostly between 70 and 270 m.y. (range 60–440 m.y.).

The wide spectrum of basin life span is remarkable. It might be

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[1] GSA Data Repository item 2004113, a more detailed listing of data and sources, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

taken as a guide to the importance of different types of basins in trapping and preserving sediment in the geologic record. However, any correlation between life span and sediment volume is complex. Different basin types have contrasting accumulation rates and preservation potential (Ingersoll and Busby, 1995), and some basins with short life spans may be repeatedly created, filled, and destroyed to build major sediment bodies. Extreme examples of this paradox are some short-lived trench basins, whose fill is repeatedly scraped off into an accretionary prism that may rival a passive margin basin in size.

BASIN GROUPS

Grouping basins by life span is informative, but less so than arranging them into genetically related groups. Such a chart (Fig. 2) suggests three such groups, and three remaining basin classes. The horizontal scale is now time, but the life-span results for each basin class (Fig. 1) have been transposed into Figure 2 to calibrate the evolution of each basin group. The ocean-basin results have been increased by 20 m.y., the average duration of the continental rifting that precedes creation of ocean floor.

Each basin group logically starts its evolution at zero time (Fig. 2), but the tapered lower time limit to each group depicts the threshold, discussed herein, at which basins become distinct entities. The upper time bound to each basin group is when it reaches its ultimate fate, for example by tectonic deformation or thermal decay. This time range is constrained by the data (Fig. 1), but the age distribution within this range is arbitrarily shown in Figure 2 as linear. Basin groups are shown ornamented according to their typical heat flow, which partly influences the style of their deformational fate: a low heat flow favors thin-skinned tectonics and a high heat flow favors thick-skinned basement-involved deformation (Rodgers, 1995; Paul et al., 1999). The following is a brief commentary on each group of basins (Fig. 2), emphasizing typical basin histories, rather than comprehensively treating all possible paths.

Basins initiated at divergent boundaries typically begin as rifts in continental crust lasting ∼10–30 m.y. Some rifts fail to diverge further; these undergo thermal subsidence to become aulacogens, developed at a high angle to eventual passive continental margins. Some intracratonic basins may develop in this way, although they typically involve several rift reactivations over several hundred million years; some may have other origins (Klein, 1995). Rifts that continue to diverge become proto-oceanic rifts and then differentiate into two passive margins flanking new ocean crust. Such basins typically last 100–200 m.y. Ocean crust, though not necessarily its sediment cover, is fated to be subducted, or trapped behind or in front of a volcanic arc. Passive margins may either develop into active margins or become the lower plate of a collisional orogen. The low heat flow through a passive-margin or old ocean basin favors thin-skinned tectonics in its fill, at least until heated deep in a collisional orogen.

Basins initiated at convergent margins are grouped into those outboard and inboard of the arc. Trench basins are the shortest lived of the outboard basins, developed mostly on oceanic crust but with fill that is either subducted or accreted on a time scale <1 m.y. The topographic trench lasts much longer, typically over tens of millions of years. Figure 2 depicts most trench fill being accreted into a subduction complex, which is overlain by trench-slope basins lasting 2–20 m.y. The accretionary complex may form the outboard edge of a forearc basin, the inboard edge of which rests on arc crust. Forearc basins typically last 10–60 m.y. Basins outboard of arcs are fated to be involved in the upper plate of collisional orogens. Being cold basins, they should be prone to thin-skinned tectonics, although the high rigidity of the crust below many forearc basins shields them from strong shortening.

Arcs host intra-arc rift basins, often with a strong strike-slip component, lasting ∼2–20 m.y. In extensional arcs, some of these rift basins develop into backarc basins floored by new mafic crust and lasting 50 m.y. or more. In ancient systems, new backarc basins may be difficult to tell from those formed by trapping parts of larger oceans. Figure 2 plots these trapped basins with the ages of their igneous crust in the range 20–70 m.y. The mafic crust of backarc basins tends to subduct if the arc system turns compressional. The high heat flow through the whole arc and backarc region makes the basins prone to thick-skinned tectonics during shortening.

Compressional arc systems tend to develop retro-arc foreland basins on their inboard flanks, lasting ∼20–60 m.y. Although these basins may develop from backarc basins, they may also form on old continental crust and are, therefore, shown as a separate basin class. Peripheral foreland basins develop on the lower plates of collisional orogens, typically on time scales of 10–50 m.y., and may also be superposed on other basin types, such as passive margins. Most retro-arc and peripheral foreland basins have low heat flow and cool basement and therefore tend to deform by thin-skinned tectonics.

Strike-slip basins are shown (Fig. 2) as a separate class. Some such basins occur along long-lived transform boundaries (e.g., Cayman Trough, Fig. 1). However, most strike-slip basins occur along faults that partition strike-slip displacement in transtensional or, more commonly, transpressional settings, particularly in arcs and collisional orogens. Here, the basins are relatively small and short lived, typically 3–10 m.y.

CONSEQUENT AND CONTINGENT FATES

A premise of the basin-fate chart (Fig. 2) is that each class of basin has one or more predictable fates, termed here consequent fates in that they ensue logically from a specific basin setting. The consequent fate of some basins is to develop into another basin class; for example, rifts evolve into passive margins or ocean basins. More commonly the fate of a basin is deformational or thermal rather than depositional. The chart (Fig. 2) suggests that these deformational fates are a consequence of the basin setting and heat flow.

A basin may also have a contingent fate, one not predetermined by the basin's tectonic setting. Two such fates are far-field shortening—basin ''inversion''—such as occurred in the Late Cretaceous North Sea (Glennie and Underhill, 1997), and thermal uplift above a new mantle plume, such as terminated extensional basins northwest of Britain in the Paleogene (Brodie and White, 1994). Both basin inversion and plume uplift are more conspicuous in rifts, aulacogens, and intracratonic basins. However, neither contingent fate is a direct consequence of basin setting in the same way that trench fill is accreted or a foreland basin is overridden by a fold-and-thrust belt. Contingent fates are genetically unrelated to formation of a basin and may spare the basin entirely.

BASIN LIFE SPANS IN THE WILSON CYCLE

The Wilson Cycle—continental rifting and ocean spreading, followed by ocean closure and continental collision—is a helpful, if simplified, way of viewing the tectonic controls on sedimentary-basin formation. The estimates of basin life span in this paper (Fig. 1) give one way of calibrating an average Wilson Cycle.

The typical rift-and-drift phase is constrained by the average life span of passive-margin basins or the combined life spans of rifts and ocean basins, i.e., ∼150 m.y. Calibrating the subduction phase is less easy. A minimum duration for an extensional subduction arc is given by the 40 m.y. life span of an average backarc basin. The typical 36 m.y. span of retro-arc basins can be added to this figure, following the model of Dewey (1980), that extensional arcs change into compressional arcs as younger ocean crust is subducted through the Wilson Cycle. Other subduction-related basins are too short lived to further

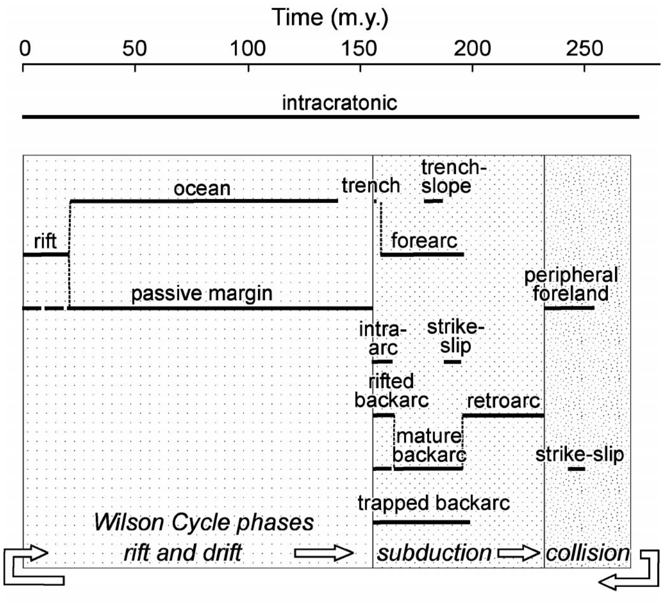

Figure 3. Average life span of basin classes used to calibrate Wilson Cycle of ocean opening and closing. Note linear time scale. Dashed lines are sequential links between basin classes that help to constrain lengths of cycle phases.

constrain the subduction phase. A proxy for the continental-collision phase is the 23 m.y. life span of an average peripheral foreland basin.

No great accuracy is claimed for the 260 m.y. duration for the Wilson Cycle indicated by totaling the durations of its component basins. It is of the correct order of magnitude for plate-tectonic cycles. However, an obvious inconsistency is that the rift-and-drift Wilson phases are longer (150 m.y.) than the subduction-and-collision phases (110 m.y.). The divergent and convergent boundaries in the present plate system have about the same length and average displacement rate, so that the average time for ocean opening should be similar to that for ocean closure. The reason for the mismatch (Fig. 3) is that basin life span is a better proxy for the Wilson phases at divergent boundaries than at convergent boundaries. At subducting boundaries, a single forearc or backarc basin may not persist through the entire subduction history, whereas in collision zones, only a fraction of the orogenic life span may be preserved in associated basins. On this reasoning, the convergent phases of the Wilson cycle should average 150 m.y. rather than 110 m.y., a testable prediction that is outside the scope of this paper.

CONCLUSIONS

Each main class of sedimentary basin has a typical life span, from the 0.1–1 m.y. of trench basins to the 200–500 m.y. of intracratonic basins. However, life span is not directly correlated with the importance of a basin type in harvesting sediment for the geologic record.

Basin life span is used to produce a genetic grouping of basins that focuses attention on the likely fate of each basin class. Basins can be succeeded by other types of basin or die by thermal decay or by tectonic deformation. A consequent fate is a logical result of a basin's tectonic setting, whereas a contingent fate is not.

The Wilson Cycle can be calibrated by using basin life spans, giving estimates of ~150 m.y. for the rift-and-drift phase, but only 110 m.y. for the subduction-and-collision phases. However, basin life spans underestimate the duration of associated subduction-and-collision systems.

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