A Second Look at the Geologic Map of China: The "Sloss Approach"

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Abstract

A key tool for geologic or tectonic reconstruction is the geologic map. When one attempts to understand an area as large and complicated as China, this tool contains more information than is optimal. The presence of too much detail can obscure important general trends. To facilitate the understanding of the major tectonic events that took place in China during the Phanerozoic, the geologic and tectonic maps of China are simplified and recast in an easily interpretable format. A methodology is presented that is similar to the one introduced by L. L. Sloss in the early days of plate tectonics and sequence stratigraphy. Each tectonic zone of China is represented by one "Sloss curve," which is a time-series representation of the geologic map. The curve shape reflects the geological response to tectonic changes. Patterns emerge when the "Sloss curves" are compared and correlated between the tectonic zones. The compiled "Sloss map" can be used as a low-pass filter of tectonic events. Two events clearly stand out across the "Sloss map" of China: the Permo-Triassic North China–South China collision, and the Cenozoic India–Eurasia collision.

Introduction

THE TECTONIC HISTORY of China is a very complicated one, characterized by amalgamation of numerous microcontinents throughout the entire Phanerozoic (e.g., Zhang et al., 1984; Hendrix and Davis, 2001). A simplified tectonic domain map is presented as Figure 1. In order to understand the chronology of events, it may be fruitful to look at the geologic record from a distance. Only by a thorough understanding of the big picture can one attempt to fully comprehend the more detailed geologic record.

With his 1963 paper, L. L. Sloss was one of the fathers of sequence stratigraphy, more than a decade before this term was introduced by Vail et al. (1977). On the eve of the plate tectonic revolution, Sloss described cycles of alternating sedimentation and erosion on a continental (Sloss, 1960, 1963), and later global (Sloss, 1976) scale. We now know that these first- and second-order stratigraphic cycles (Vail et al., 1977) mainly are the result of the breakup and assemblage of supercontinents, and of the related periodicity in the rate of ocean spreading and the volume of mid-oceanic ridges (e.g., Flemming and Roberts, 1973). In order to reconstruct the depositional cycles, and to correlate them across the continents, Sloss applied a conceptually simple

method, which is similar to the one that will be used in this paper for the description of the tectonic history of China. Therefore, I term it the "Sloss method."

L. L. Sloss used isopach maps of the United States, of Canada, and of the USSR to calculate the preserved areal extent and volume of each of the stratigraphic units of the maps. Converting these units to physical time by means of the geological time scale, he obtained depositional time series, which he found to be remarkably similar for the three areas studied (Sloss, 1976). Unfortunately, no isopach atlas exists that covers the entire territory of China. Instead, I use the digitized geologic and tectonic (Fig. 2) map at a scale of 1:5,000,000 (USGS Open-File Reports 97-470F and 97-470C). Although we have the disadvantage of poorer data quality, we also have advantages that were not available to Sloss. Computing power has increased tremendously since 1976. The tools of GIS and statistical analysis prove to be very useful for our purposes.

The Method

For each of the tectonic zones, the area covered by rocks of a certain stratigraphic age was calculated as a percentage of the total area of the tectonic zone. Next, these data were converted into time
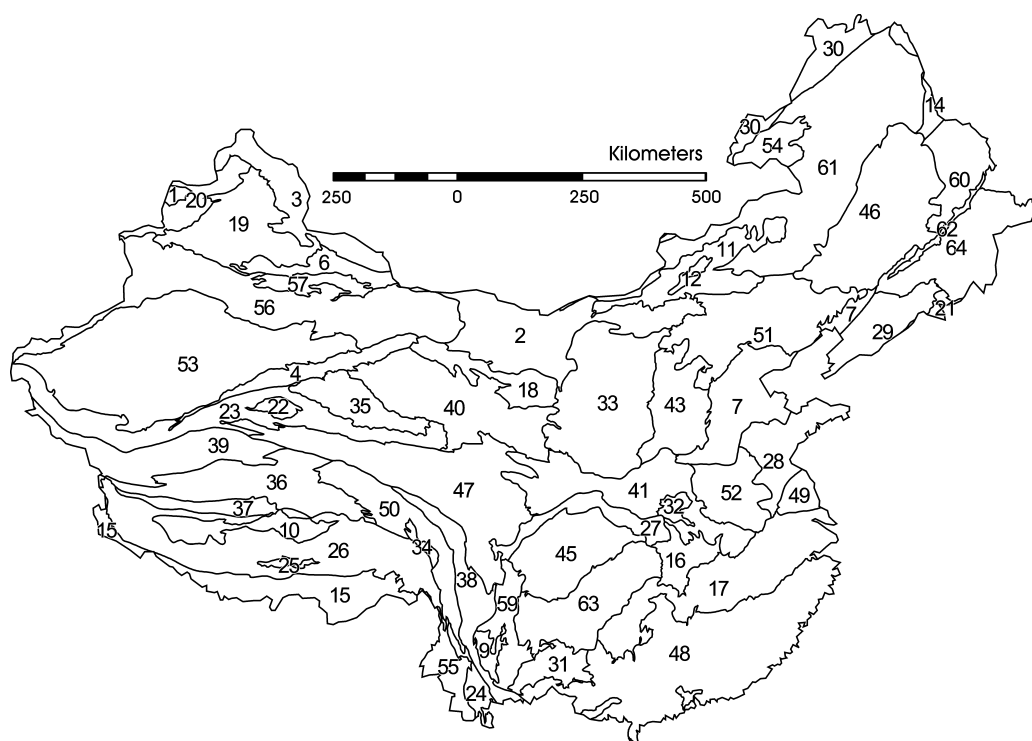
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FIG. 1. The tectonic map of China, based on USGS Open File Report 97-470C (Wandrey and Low, 1998) and 97-470F (Steinshouer et al., 1998). Legend: 1 = Alakol Basin; 2 = Alashan Yinshan; 3 = Altai-Sayan fold belt; 4 = Altunshan fold belt; 5 = Beibuwan Basin; 6 = Bogdashan fold belt; 7 = Bohaiwan Basin; 8 = Bose Basin; 9 = Chuxiong Basin; 10 = Cuoqing Lupola Basin; 11 = Erlian Basin; 12 = Erlian uplift; 13 = Gobi Basin; 14 = Heilongjiang Basin; 15 = Himalaya; 16 = Jainghan Basin; 17 = South Jiangsu fold belt; 18 = Jiuquan Minle Wuwei; 19 = Jungger Basin; 20 = Karamay thrust belt 21 = Korean craton; 22 = Kumukulig Basin; 23 = Kunlunshan fold belt; 24 = Lanping Simao Basin; 25 = Lhasa Basin; 26 = Lhasa terrane; 27 = Longmenshan; 28 = W. Luxi Jiaoliao uplift; 29 = E. Luxi Jiaoliao uplift; 30 = Mongol-Okhotsk [fold belt?]; 31 = Nanpanjiang Depression; 32 = Nanyang Basin; 33= Ordos Basin; 34 = Qabdu Basin; 35 = Qaidam Basin; 36 = Qiangtang Tanggula Basin; 37 = S. Qiangtang terrane; 38 = E. Qiangtang terrane; 39 = W. Qiangtang terrane; 40 = Qiliangshan fold belt; 41 = Qinling Dabieshan; 42 = Sanshui Basin; 43 = Shanxi Plateau; 44 = Shiwan Dashan Basin; 45 = Sichuan Basin; 46 = Songliao Basin; 47 = Songpan Ganzi fold belt; 48 = South China fold belt; 49 = Subei Yellow Sea Basin; 50 = Sulongshan fold belt; 51 = Taihangshan Yanshan; 52 = Taikang Hefei Basin; 53 = Tarim Basin; 54 = Temtsag Hailar Basin; 55 = Tenasserim Shan; 56 = Tian Shan–Bei Shan; 57 = Turpan Basin; 58 = Ushumun Basin; 59 = Xichang Yunnan; 60 = E. Yinshan uplift; 61 = W. Yinshan uplift; 62 = Yitong graben; 63 = Yunnan Guizhou Hubei; 64 = Zhangguangcailing.

series by means of the time scale of Harland et al. (1990). The time resolution of the geologic map is rather poor and not uniform, with most units defined at the chronostratigraphic systems level, while some span as much as an entire era. To solve this problem, the following strategy was used: given overlapping stratigraphic units 1 and 2, of duration S1 and S2, respectively, A_{S2}^{S1} is the areal contribution of unit 2 to the part of the "Sloss curve" that overlaps in time with unit 1:

$$A_{S2}^{S1} = A_{S2}^{S2} \times \left(\frac{S1}{S2}\right) \tag{1}$$

The use of equation 1 is illustrated by Figure 3. We will use it for calculating the "Sloss map" of China, which is shown in Figure 2.

For the western United States, a GIS version of the geologic map (at a scale of 1:2,500,000) is available, in a similar format as the geologic map of China (King and Beikman, 1974). A Sloss curve was calculated for a rectangular area, located between
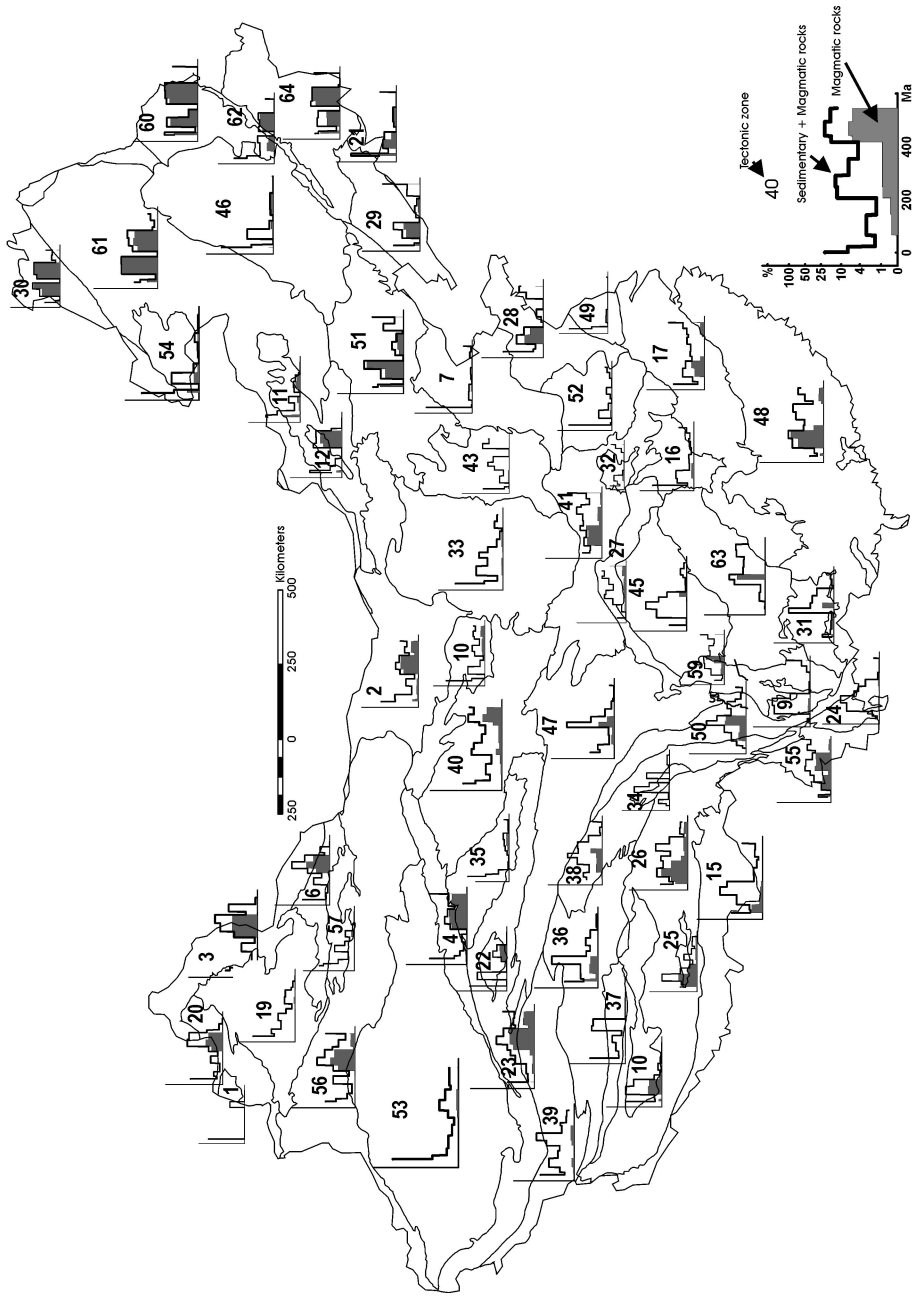
FIG. 2. The Sloss map of continental China summarizes both the tectonic and the geologic map. The numbers indicate the tectonic zones, as specified by Figure 1. Some tectonic zones were omitted if they were too small for the calculation of a meaningful Sloss curve. In each of the Sloss curves, the black line represents the percentage of the total area (on a logarithmic scale) represented by rocks of a certain age (on a linear scale) in the Phanerozoic. The area shaded dark grey under the curve represents the percentage covered by magmatic rocks (see inset).
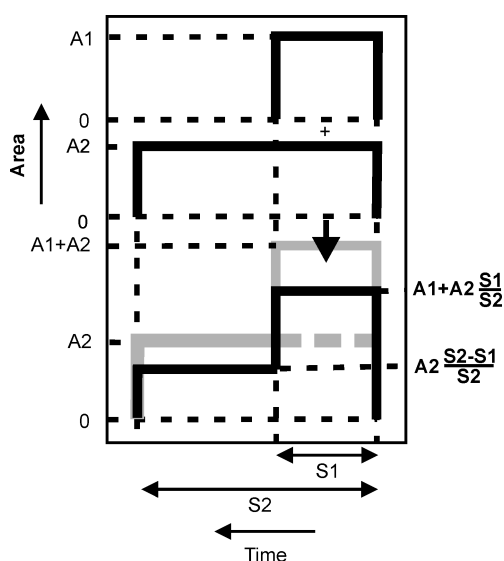
FIG. 3. If the total area of the geologic map that is labeled S1 is A1, and the stratigraphic subdivision named S2 covers an area A2, the corresponding value of the Sloss curve (black curve, lowermost part of the figure) for each elementary time step (e.g., S1) is a function of the relative time overlap, and given by equation 1 of the text.
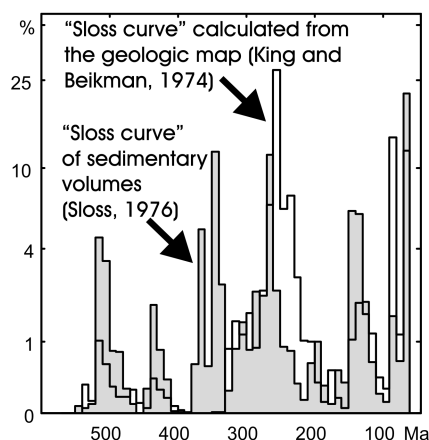

FIG. 4. Comparison of the Sloss curve of the western United States (rectangular area between 39° N/100° W and 49° N/114° W), as calculated from the geologic map (King and Beikman, 1974) (black curve), with the curves of sedimentary volume published by Sloss (1976) (grey area) for the same area. Because two different data sources were used, it was necessary to re-calculate the Sloss curves for identical time steps. Not surprisingly, the height of the peaks differs between the two curves in most cases. This is especially clear during the Paleozoic, which is especially affected by the "blanketing effect." The important thing to remember about this figure is that the major peaks and troughs are located at approximately the same times. Thus, the geologic map can be used as a proxy for the isopach map.

39° N, 100° W and 49° N, 114° W and compared to the curves that were based on isopach maps for the same area (Sloss, 1976). Thus, the validity of the method proposed above could be tested. The results of this exercise are shown on Figure 4. For reasons that are discussed further below, the fit is not perfect. Nevertheless, most depositional peaks are located at the same times. Taking into account these remarks, the Sloss curves of Figures 2 and 4 represent an important simplification and abstraction of the geologic map. We will use them to compare the different tectonic zones of China, and reconstruct their history. Such analysis is reliable because all Sloss curves on Figure 2 are based on the same geologic map, using the same stratigraphic subdivisions. It would be more dangerous to make inferences based on a single Sloss curve, or use the method to compare different data sets, which is what was done for the construction of Figure 4. Figure 2 shows some interesting and tectonically meaningful features that will be interpreted in the discussion section of this paper.

Limitations and Uncertainties of the Method

The most important problem Sloss (1976) pointed out in his method was the incompleteness of the geologic record: erosional processes progressively remove greater fractions of the rock record with time. Because the analysis that is presented in this paper is not based on isopach maps, but on the geologic map, these problems are aggravated and additional problems arise.

(1.) First and foremost, not only erosional processes, but also sedimentary processes obscure the more distant geological past. It is possible for a relatively thin cover of horizontally deposited sediments to completely dominate the geologic map of an area, even in cases where older formations represent much larger volumes and thicknesses. This "sedimentary blanketing effect" is illustrated by Figure 5. The importance of the "blanketing effect" dramatically decreases with increasing age. Older geological formations are more likely to have been affected by previous stages of tectonism, which
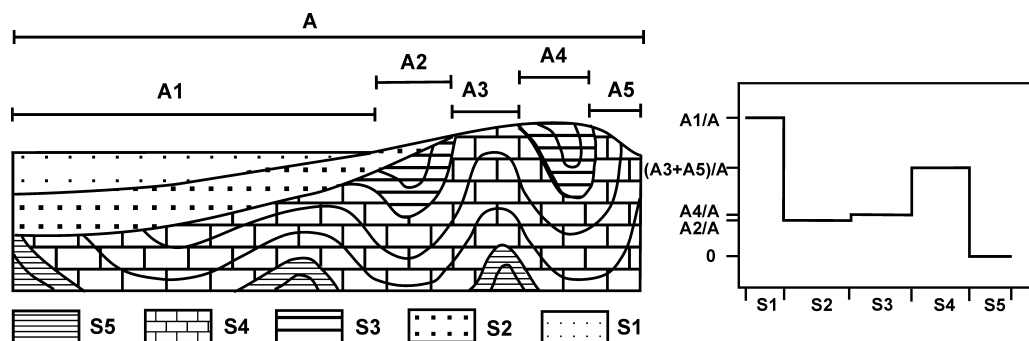
FIG. 5. Illustration of the sedimentary "blanketing effect": steeply tilted layers make smaller outcrops, even though they can have greater thickness and volume than their subhorizontal sedimentary cover ("blanket"). The more deformed a region is, the better the geologic map, and its corresponding Sloss curve represents the volumetric distribution of the strata.

cause folding and tilting. These processes improve the quality of outcrop area as a proxy for sedimentary thickness and volume (Fig. 5). Therefore, the "Sloss-like methodology" should be more reliable for the more distant past. However, there is a tradeoff with the time resolution of the geologic map, which generally decreases with age. The Precambrian is only subdivided into two parts—Archean and Proterozoic. For this reason, the Precambrian has been omitted from the map of China in Figure 2.

(2.) Sloss included lithological data in his analysis. The GIS version of the geologic map of China distinguishes between sedimentary and magmatic rocks, but does not subdivide the sedimentary rocks. Lithologies obviously can provide important information regarding the tectonic setting of an area, but they are less easily represented by numbers that can be objectively compared. Also Sloss based his conclusions mostly on the numerical values of volume and preserved area. On Figure 2, the area under the Sloss curves covered by magmatic rocks are shaded dark grey.

Discussion: Tectonic History of China as Illustrated by its Sloss Map

Figure 6 shows how the 64 tectonic zones of China can be grouped into a smaller number of tectonic "regions." This grouping is in close agreement with the tectonic zonation of Zhang et al. (1984) and Yin and Nie (1996). This section will discuss how the Sloss map can provide a semi-independent confirmation of its validity. On Figure 6, the tectonic affinities are indicated by different hatching pat-

terns. The hatching density further divides the tectonic groups in subgroups that are more convenient to discuss together. It is important to note that some of the tectonic zones were assigned to a tectonic group in a rather arbitrary way. Generally, this is the case for suture zones. For example, the Tian Shan was considered as part of the "northern tectonic region." However, we also could have put this range in the Tarim-Qaidam block, because the Tian Shan contains fragments of both tectonic groups. Similarly, the Qinling-Dabie zone was assigned to the North China block, but being the welding zone with the South China block, it could just as well have been made part of the latter. The only "suture zone" for which an exception was made is the vast Songpan Ganzi fold belt. A special discussion will be dedicated to this zone, and its relationship with the surrounding tectonic blocks (see the section dealing with Central China).

Northern tectonic region

The northern tectonic region consists of a number of microcontinents and early Paleozoic island arcs. These were accreted to the southern margin of the Siberia-Kazakhstan plate and to the northern margin of the Tarim–North China block prior to and during the final collision between these two, which occurred diachronously from the Carboniferous (west) until the Late Permian (east) (Yin and Nie, 1996). The northern tectonic region recorded changes in the regional tectonic stress field, induced by distant accretionary events. During the Mesozoic and Cenozoic, Paleozoic fold belts were reactivated several times as complicated systems of

FIG. 6. The tectonic map of China, hatched according to tectonic affinity. Some tectonic groups are further divided by the density of the hatching where this facilitates discussion of the tectonic history in sections of the text.

intracontinental mountain ranges and sedimentary basins. Although its tectonic zones have a similar (Paleozoic) tectonic history, the northern tectonic region is so large that we will continue our discussion by further dividing it into an eastern and a western part.

Northeast China. Northeast China is part of the Mongolian accretionary fold belt, which is a collage of Ordovician to Early Permian island arcs, blueschist-bearing assemblages, Paleozoic ophiolites, and possible microcontinental blocks (Davis et al., 2001). These tectonic settings stand out in the Sloss curves of Figure 7 by the great relative importance of magmatic lithologies, which are shaded black. During the Late Permian and Early Triassic, the Mongolian arc terrane was finally welded together with the North China craton along the Suolon suture (Yin and Nie, 1996; Davis et al., 2001). On the Sloss map,

this event is represented by a subsequent absence of deposits during the Triassic, which is probably due to the compression and mountain building that followed collision. During the Late Triassic, the controversial Mongolo-Okhotsk ocean opened to the north of the Mongolian arc terrane. This ocean started subducting both to the north and to the south, causing a continued importance of magmatic rocks in the Sloss curves (Fig. 7) (Yin and Nie, 1996). During the Jurassic and the Cretaceous, the Suolon suture was reactivated as the Yanshan fold and thrust belt, on the northern margin of the North China block (Davis et al., 1998, 2001). This will be discussed in more detail later. Important to note here is that one of the hypotheses for the driving force behind this reactivation is the Cretaceous closure of the Mongolo-Okhotsk ocean (Zonenshain et al., 1990; Yin and Nie, 1996; Davis et al., 1998, 2001).
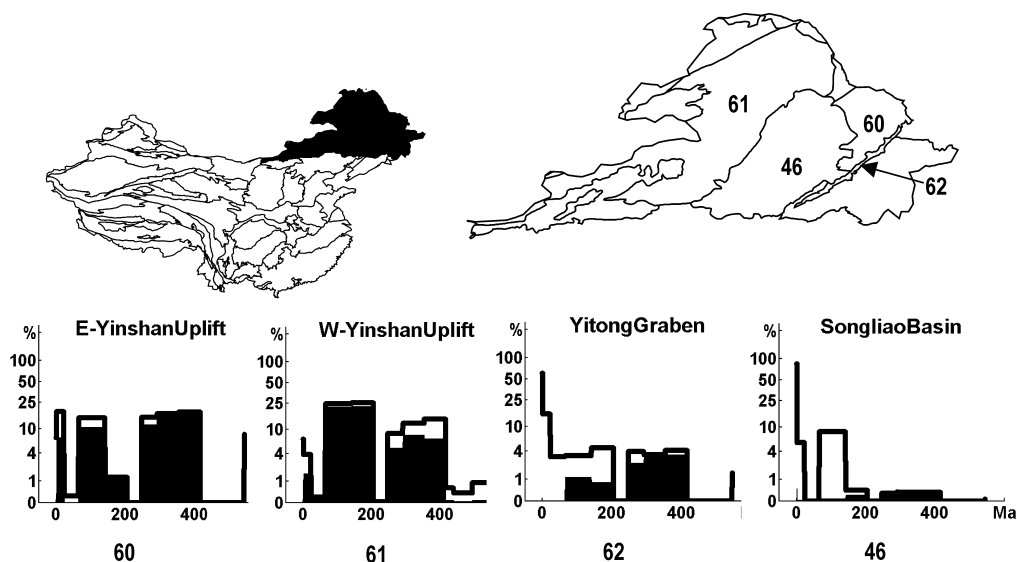
FIG. 7. Northeast China is a tectonic collage of accreted late Paleozoic terranes. It is delimited to the south by the Permo-Triassic Suolon suture, and to the north by the Cretaceous Mongolo-Okhotsk suture. The importance of subduction processes during most of the history of this region is reflected by the large contribution of magmatic rocks to the Sloss curves. During the Mesozoic, large sedimentary basins formed, whereas the Suolon suture was reactivated south of it, to form the Yanshan fold belt. The Paleogene is characterized by a dip in the Sloss curves except for the Yitong graben, which indicates that this feature is at least that old.

Alternatively, also the collisions that occurred on the southern margin of the Asian continent (notably the Cretaceous accretion of the Lhasa block), could have been responsible for the Yanshan compression (Graham et al., 2001). Curiously, this compression also was associated with basin-forming extension in the Mongolian arc terranes (Davis et al., 2001; Graham et al., 2001). Examples of such basins are the Hailar Basin and the Songliao Basin, which may have been caused by Pacific backarc extension, or by gravitational collapse of the Late Paleozoic orogen (Graham et al., 2001). This apparent paradox can be reconciled by partitioning of the Gobi extensional province from the contractional Yinshan-Yanshan orogenic belt by escape-tectonic strike-slip faults, such as the East Mongolian Zuunbayan fault, which would be associated with the coeval collisions on the southern Asian and Mongolo-Okhotsk margins (Graham et al., 2001). During the Paleogene, all the Sloss curves of Northeast China show a dip, which could be a distant result of the India-Eurasia collision, or alternatively, be caused by changes in the Pacific plate subduction regime. The only Sloss curve in Northeast China that does show Paleogene sedimentation of any significance is the Yitong gra-

ben, which suggests that this feature is at least that old (Tian and Du, 1987).

Northwest China. The pre-Devonian history of Northwest China is poorly understood. Several microcontinents and island arcs were drifting around on the subducting Turkestan ocean that separated the Tarim–North China block from Siberia-Kazakhstan (Heubeck, 2001). Between the Early and the Middle Devonian, southerly sourced clastic sediments were deposited along the passive continental margin of North Tarim (Yin and Nie, 1996). These rocks presently make up the southern Tian Shan; thus the latter does not really belong to the "northern tectonic region." During the Carboniferous, two more components of the Tian Shan were welded to the Tarim block: (1) the central Tian Shan block, a microcontinent with Precambrian basement; and then (2) the northern Tian Shan and Junggar blocks, a post-Devonian arc terrane (Zhou et al., 2001). The collision of the Junggar arcs and the Devonian Altai arcs with the Tarim–North China block in the Carboniferous–Early Permian marked the beginning of the diachronous closing of the Turkestan ocean, which eventually led to the formation in the northeast of the Permo-Triassic fold belt.
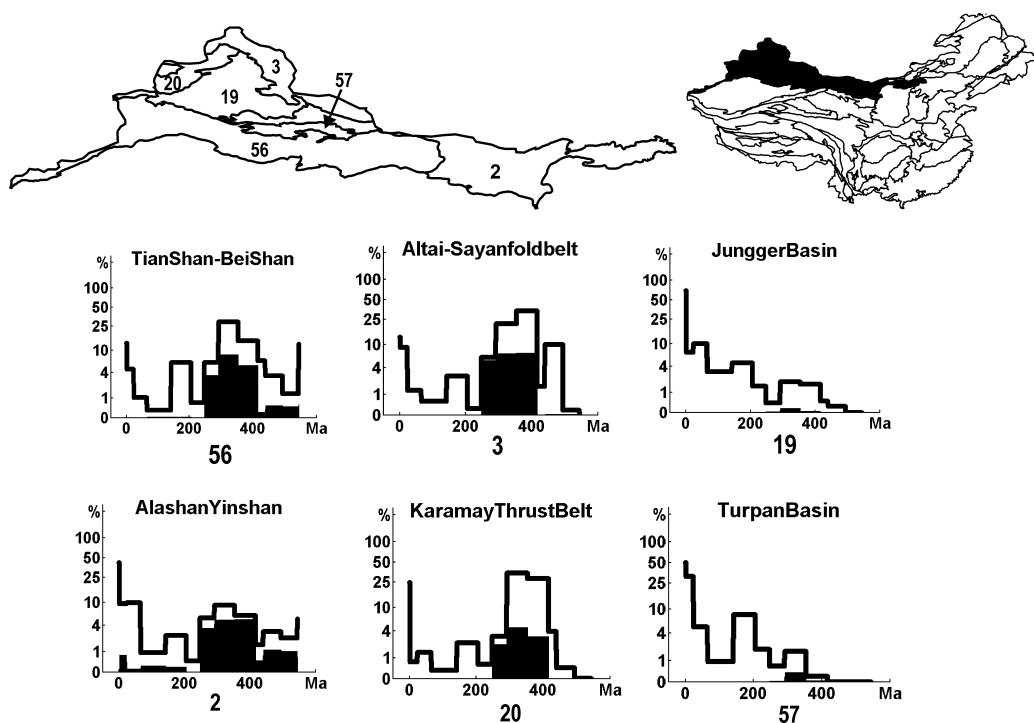
FIG. 8. Very similar to Northeast China, Northwest China also is composed of a number of microcontinents and island arcs that were accreted during the Paleozoic. Magmatic rocks dominate the Sloss curves until the Carboniferous–Permian, which corresponds with the final closure of the Turkestan ocean and the formation of the ancestral Tian Shan. In contrast with the Northeast (Fig. 7), there is no post-Paleozoic magmatism. The Sloss curves of the fold belts all show a Triassic dip, a Jurassic high, a Cretaceous dip, and a Cenozoic high. These reflect the repeated reactivation of this region due to ongoing collisions on the southern margin of the Asian continent.

After its formation in the Carboniferous, the Tian Shan, in a very similar way to the Yinshan-Yanshan, would be reactivated during the Late Mesozoic and the Late Cenozoic, as a result of collisional events that occurred far to the south of the range (Dumitru et al., 2001). Examples of such events are the Jurassic Qiangtang-Tarim collision and the Cretaceous Qiangtang-Lhasa collision. Furthermore, the Cenozoic Himalaya orogeny has caused stresses that are transferred deep into the Asian continent. They have made the modern Tian Shan the most spectacular of all intracontinental mountain belts, with elevations of up to 7,400 m, at more than 1,000 km from the suture zone (Molnar and Tapponnier, 1975).

The Sloss curves of different portions of Northwest China (Fig. 8) share numerous characteristics with each other, indicating a common tectonic history since the Carboniferous. The Late Paleozoic is

characterized by voluminous magmatic lithologies, which represents the subduction-dominated setting of many of the terranes of this area. From the Permian onward, magmatism ceased, in marked contrast with the tectonic zones of Northeast China. Indeed, in the northeast the existence of the Mongolo-Okhotsk ocean, and the proximity to the subducting Pacific Ocean, continued to generate magmas throughout the Mesozoic and Cenozoic, which was not the case for northwest China. Another characteristic of most zones of the Sloss map of Northwest China is a pronounced dip during the Triassic, which was probably caused by mountain building that followed closure of the Turkestan ocean, with the addition of the compressional stresses caused by the southerly Qiangtang-Tarim collision. The Jurassic shows up as a peak in most Sloss curves. This could represent post-orogenic subsidence ("collapse"). The Cretaceous is a dip
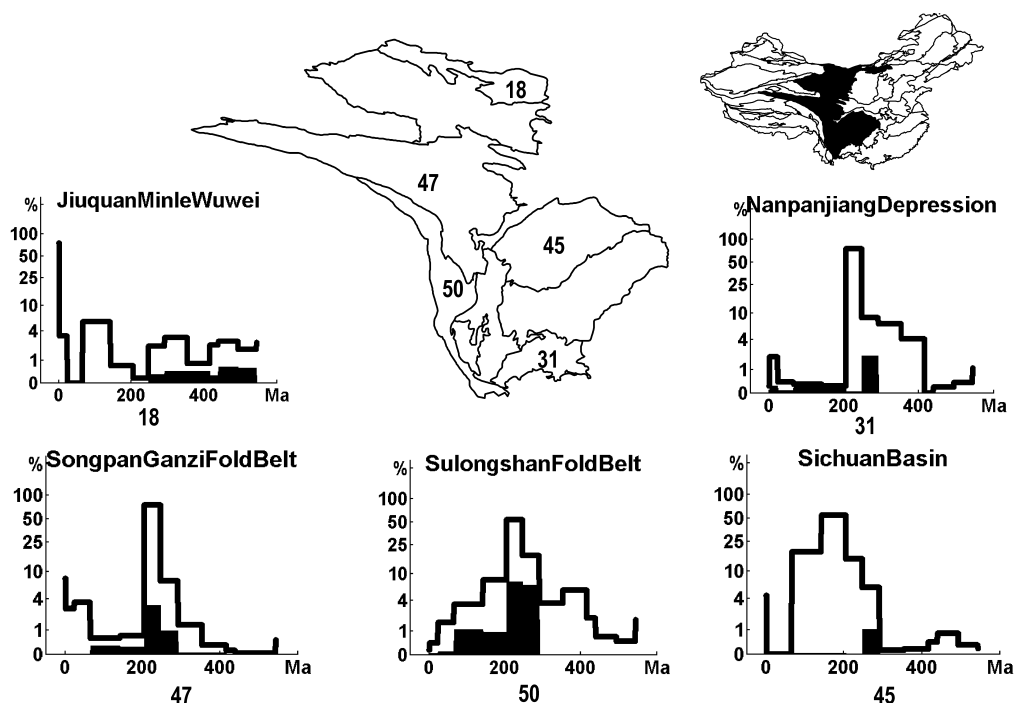
FIG. 9. The Sloss map of Central China shows a very characteristic peak of sedimentation and magmatism in the Triassic for the tectonic zones south of the Songpan Ganzi complex. This peak is caused by the diachronous collision between the North China and South China blocks (Zhou and Graham, 1996b). The zones north of the suture zone show a lack of sedimentation at the same time, possibly related to the uplift and compression caused by continental collision.

again, corresponding to Late Mesozoic reactivation of the Tian Shan that is detected by a cluster of Cretaceous apatite fission track ages (Bullen et al., 2001; Dumitru et al., 2001). Finally, the Cenozoic Sloss curve shows an increase. This is caused by a strong "blanketing effect," and reflects the formation of large foreland basins (e.g, Junggar, Turpan) between the different mountain ranges (e.g., Tian Shan, Bogda Shan). The structural and stratigraphic relief between these coexisting tectonic elements can attain several thousand meters over distances of just a few tens of kilometers.

North China block

The Tarim block and the North China craton are often postulated to have behaved as a single tectonic block since at least the early Paleozoic (e.g., Zhang et al., 1984; Yin and Nie, 1996). Others have suggested that they were separate blocks until the Permo-Triassic closure of the Turkestan ocean (Zhou and Graham, 1996a; Yang et al., 1997). Yet the Tarim block and the North China craton are only

connected by a very narrow strip. This "problem" is solved by restoring ~ 400 km of Cenozoic sinistral displacement along a controversial Altyn Tagh–Alxa–East Mongolia fault (Yue and Liou, 1999; Yue et al., 2001). In this section, we discuss the North China craton *sensu stricto*, which is the eastern part of the North China–Tarim block. The North China craton is bordered to the north by the Permo-Triassic Suolon suture, which was reactivated during the Jurassic as the Yanshan intracontinental fold belt (Davis et al., 1998, 2001). To the southwest, the North China craton is sutured against the Qaidam block along the Qilian Shan; the suture marks a collisional event of Devonian age. Due east of the Qilian Shan is the Qinling Dabie Shan, which represents the Permo-Triassic collision of the North China block with the South China block (Yin and Nie, 1996; Zhou and Graham, 1996b). To the southeast, the North China block is offset by the sinistral Tan Lu fault system.

Although named a "craton" (it has Archean basement), the North China tectonic group under-

went substantial internal deformation over the course of its Phanerozoic history. The Sloss curves of the North China craton do not tell a simple story. Important information has been obscured by the "blanketing effect." This is especially the case for the Cenozoic Bohai rift basin. During the Late Triassic, this zone roughly corresponded to the "Huabei plateau," which was the result of continuing convergence after the collision of South China with North China (Yin and Nie, 1996). Sediments derived from this topographic high were deposited in the neighboring Shanxi and Ordos basins, where they are responsible for a Triassic peak in the Sloss curves. This is a feature that will be seen more often in the Sloss map of central China (discussed below; Fig. 9).

South China block

The South China block is a relatively stable craton (also called the Yangtze craton) that has a relatively insensitive Sloss curve. In the Jiangsu and South China fold belts, all stratigraphic ages are represented approximately to an equal degree, with a small preference to the Quaternary due to the "blanketing effect." The Sloss curves of the western part of the South China tectonic group show a distinct peak in the Triassic. This marks the collision of the South China block with the North China block, as will be discussed below.

Tarim-Qaidam

As previously discussed, disagreement exists as to whether or not the Tarim block and the North China craton were separate tectonic entities before the Permian. A similar controversy exists about the Qaidam block. Some have suggested that it was part of the Tarim before being cut off and displaced by the Altyn Tagh fault (Zhou and Graham, 1996a; to some extent also Yin and Nie, 1996), whereas others think that the two to represent separate tectonic blocks (e.g., Zhang et al., 1984). The discovery of a Middle Paleozoic suture zone in the Altyn Tagh favors the latter point of view (Sobel and Arnaud, 1999). After the Qaidam and Tarim blocks were welded together, an extensive, continuous, late Paleozoic–early Mesozoic Kunlun magmatic arc developed along their southern margin. This arc died during the Triassic collision of the Tarim-Qaidam block with the Qiangtang block.

The closure of the ocean basin that existed between the Tarim-Qaidam block and the Qiangtang block is marked by the abrupt ending of the (black-shaded) magmatic area under the Sloss curve of the Kunlun tectonic zone. The same is true for the Altun Shan, where magmatism ended with the closure of the ocean that existed between Tarim and Qaidam. Due to the "blanketing effect," little can be said about the Sloss curves of the Qaidam and Tarim basins themselves. In this case, it would be particularly valuable to have access to isopach maps such as the ones Sloss (1976) used.

Central China, Songpan Ganzi, and the Permian–Triassic North China–South China collision

The most representative tectonic element for this region is the Songpan-Ganzi fold belt. This tectonic zone is characterized by a striking depositional peak in the Triassic (Fig. 9). This peak can be recognized slightly less spectacularly in the zones immediately to the south of Songpan-Ganzi (e.g., the Sichuan Basin, Sulong Shan). Sloss (1963, 1976) was not the first person to recognize that the Triassic was a lull in continental sedimentation. It followed immediately after the last (Variscan) stages of the assemblage of the Pangea supercontinent, and is characterized by very low global sea level (Vail et al., 1977). Hence, the abundance of Triassic deposits in the tectonic zones of Central China must indicate an important tectonic event. This event is the diachronous suturing of the North and South China blocks (Zhou and Graham, 1996b). North of Songpan-Ganzi (e.g., Altun Shan), the Triassic shows up as a low point in the Sloss curve. This could either be the result of the worldwide sea-level drop described above, or alternatively, be caused by the same events that caused the Triassic peak in and south of Songpan-Ganzi. Indeed, if the Triassic orogeny was the result of northward underthrusting of the South China block under the North China block, it seems likely that the zones north of the suture zone would be uplifted, whereas the southern zones would flexurally subside. A modern-day analogue to this would be the association on either side of the Indus-Tsangpo suture zone of the North Indian Ganges foreland basin, and the Tibet-Qinghai Plateau.

Southwestern China

The Qiangtang block drifted off from Gondwana some time during the Paleozoic (Yin and Harrison, 2000). During the Triassic, the ocean that separated the Qiangtang terrane from the Asian continent started subducting beneath it. The northern margin of the Qiangtang terrane became an active one,
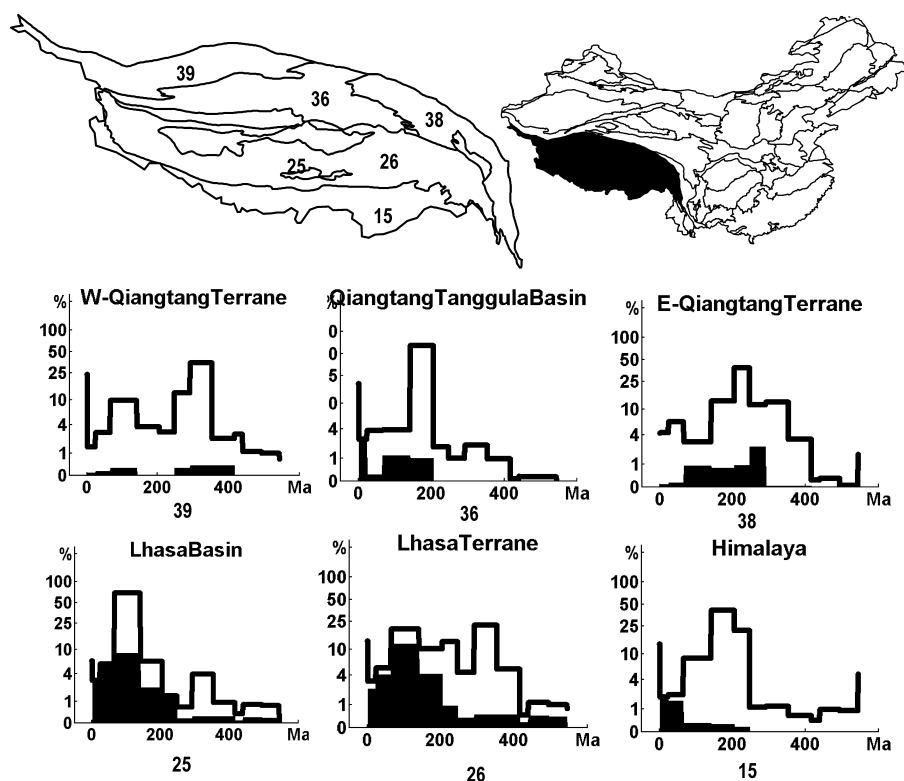
FIG. 10. The Tibet Plateau consists of three tectonic blocks—the Qiantang, Lhasa, and India blocks. Qiangtang underthrusted the Kunlun block in the Late Triassic, which shows up as a peak in its Sloss curve. Subsequently, the Lhasa block collided with the Qiangtang block, after the closure of an oceanic basin that was associated with a magmatic arc and a substantial area of black under the Sloss curve. Finally, the southern margin of the Lhasa block became an active one (represented by a predominantly black shaded Sloss curve), until the final collision with India, which caused a dip in the Cenozoic curves of both the Qiangtang and the Lhasa block.

which is reflected in an increase of the magmatic area under its Sloss curves (Fig. 10). Almost immediately following the Permo-Triassic collision of South China with North China, the Qiangtang-Indochina block was underthrusted by the amalgamated South China and Qaidam-Tarim blocks along the Jinsha suture (Chang et al, 1986; Yin and Nie, 1996; Yin and Harrison, 2000). The Songpan-Ganzi remnant ocean basin was trapped in the triangular space between the three aforementioned blocks. The Triassic peak in the Sloss curves of the Qiangtang block attest to this event (Figs. 9 and 10). Although subduction-related magmatism stopped in the Kunlun, it continued in the Qiangtang block, along with the approach from the south of the Gondwana-derived Lhasa block. The Lhasa block collided with the Qiangtang block along the Banggong-

Nujiang suture during the Cretaceous (Allègre et al., 1984; Dewey et al., 1988; Yin and Nie, 1996; Yin and Harrisson, 2000). Whereas the underthrusted Qiangtang block was deformed and uplifted (marked by a relative low in its Sloss curves), the underthrusting Lhasa block underwent flexural subsidence and is generally characterized by a "Sloss peak." After the collision of the Lhasa block with the Qiangtang block, the oceanic crust that separated the Lhasa block from the Indian subcontinent subducted beneath the Lhasa block, which resulted in extensive magmatic activity and the development of the Gangdese batholith (Allègre et al., 1984; Yin and Harrison, 2000).

At approximately 45 Ma, India finally collided with Asia along the Indus-Tsangpo suture (Le Pichon et al., 1992). This led to the intensely

studied, but poorly understood, Himalaya-Tibet orogeny. The Tibet-Qinghai Plateau is believed to have resulted mainly from this final collision, although it has been suggested that a pre-existing plateau formed after the Lhasa-Qiangtang collision (Murphy et al., 1997). The present day Tibet-Qinghai Plateau comprises the Lhasa terrane, the Qiangtang terrane, and to some extent the Kunlun–Qaidam–Qilian Shan tectonic group. At the same time, the Himalaya-Tibet orogeny reactivated many of the tectonic zones and groups that have been discussed in previous paragraphs. This is the case for the Tian Shan and the Altai, but also for the Altun Shan, which appear to have acted as a zone of weakness that became the preferred locus for the continental-scale Altyn Tagh sinistral strike-slip fault. The Kunlun, Xianshui-He, and Red River faults roughly follow the Kunlun-Anyemaqen, Jinsha, and Banggong-Nujiang sutures, respectively (Tapponnier et al., 2001). Thus, fault reactivation seems to be a major factor in the deformation of the Chinese tectonic "jigsaw puzzle." The translation of this in terms of Sloss curves is a trivial one: topographic depressions cause Cenozoic peaks, whereas areas of high relief show a dip in the Cenozoic Sloss curve. These signatures can be seen all over China, and perhaps even affect the Pacific margin (e.g., Jolivet et al., 1990).

Conclusions

I have developed a method for representing a two-dimensional geologic map by a one-dimensional depositional time series, similar to the way L. L. Sloss represented the geologic maps of North America and eastern Europe (Sloss, 1976). Going one step further, the geologic map and the tectonic map of China were united into one "Sloss map." Despite limitations and assumptions of the method, the Sloss map proves useful for recognizing the most important tectonic events of Phanerozoic China, and for delimiting tectonic regions, which can comprise multiple tectonic zones. The Permian–Triassic North China–South China collision and the Cenozoic India-Eurasia collision stand out especially clearly. Also, the difference between stable cratons and tectonically more sensitive accretionary fold belts can easily be recognized.

Major improvements could be made with the incorporation of isopach maps, rather than ordinary geologic maps. Other welcome changes would be increased time resolution, and the addition of more

lithological parameters to the geologic map. If all these conditions were fulfilled, it might be possible to fully automate the interpretation of the Sloss map by means of a statistical correlation analysis. If extended to other continents, the "Sloss analysis" could prove to be as useful in tracing and describing the breakup of continents as it is with continental accretion, which I have demonstrated in this paper with China's history of amalgamation. The first places to examine in the case of China would be Gondwana, and the southern margin of the Tethys. Indeed, most of the tectonic blocks of Figure 2 originally drifted off from continental areas now constituting India and Australia (Şengör and Natal'in, 1996). The methodology described in this paper might prove to be a good first-order way of detecting such associations.

Another application of the "Sloss method" in its present form would be the study of orogenic terranes. If geologic maps exist in a GIS form, the Sloss curve derived from the geologic map could be used as a proxy for the isopach map, as was suggested in Figure 4. Doing this may yield insight into the evolution of rates of deposition until the time of collision, which is important for understanding the mechanisms of mountain building.

Acknowledgments

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