are compatible with the cylindrical volume diffusion at a scale of the crystal diameter (Hames and Bowring, 1994, and references cited therein). Minor radial age gradients may exist in all of the samples; however, we effectively "averaged out" such variations by sampling a single size fraction and by using the muscovite total gas ages as the best approximation of the time of cooling through a fixed isotherm. Because of the similar size, composition, and cooling rate, we are confident that all of the muscovites have a very similar closure temperature.

Finding the heat source responsible for the age variation in the Presidential Range, that Oliver suggests is due to thermal relaxation of a perturbed geotherm, is problematic. Our muscovite ages are too old to be related to the Mesozoic White Mountain plutonic-volcanic series and too young to be related to the voluminous Carboniferous-Devonian two-mica granitoids in the region. The systematic radial increase in muscovite ages away from the contact with the Sebago batholith (see Eusden and Lux, 1994, Fig. 1) is suggestive of a thermal perturbation caused by the intrusion of this pluton. However, Aleinikoff et al. (1985) determined the age of the Sebago to be ~325 Ma. Therefore, our muscovite ages would be too young to be thermally related to this intrusion. Another possibility is that the "chrontour" pattern around the Sebago was created by Triassic structural doming of a subhorizontal "fossil" isothermal surface.

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Exhumation of the Dabie Shan ultra–high-pressure rocks and accumulation of the Songpan-Ganzi flysch sequence, central China: Comment and Reply

COMMENT

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Nie et al. (1994) proposed that the Triassic Songpan-Ganzi flysch represents the eroded 100-km-thick overburden of the Dabie Shan ultra–high-pressure rocks. Nie et al. present lithostratigraphic sections of the Triassic flysch and estimated that the rock volume in this flysch is equivalent to the volume of rocks that overlaid the ultra–high-pressure rocks at the time of their metamorphism. On this basis, Nie et al. (1994) suggested that the Dabie Shan coesite-bearing rocks were unroofed by erosion.

The presence of coesite in the Dabie Shan orogenic belt indicates that collision resulted in burial of crust to a depth of more than 90 km. The exact shape of the Triassic orogenic wedge is not known, but it is reasonable to assume that the rock column above the Dabie Shan coesite included high- and medium-grade rocks such as eclogites, blueschists, granulites, and amphibolites. Unless the depth to the Moho reached 100 km, mantle peridotites were also present in the overburden. Exhumation by erosion is expected to unroof progressively deeper levels of the orogenic wedge, and in the case of the Dabie Shan the combined proportion of high-grade rocks and peridotites in the eroded sequence should reach about 70%.

A major obstacle to the interpretation of Nie et al. (1994) is that neither high-grade rocks nor relics of a high-pressure mineralogy were described in the Songpan-Ganzi flysch. The absence of these constituents implies that direct evidence linking the unroofing and exhumation of the Dabie Shan with the Songpan-Ganzi flysch are still missing. Several factors may have reduced the quantities of high-pressure and peridotite relics in the source region as well as in the flysch. It is possible that only a part of the subducted rock sequence reacted during progressive metamorphism (Austrheim, 1994), that blueschists and eclogites were partly overprinted during decompression and became less abundant, and that relics completely disintegrated because of weathering. Nevertheless, heavy-mineral analyses of flysch samples may prove useful in clarifying the nature and evolution of the source region (see, e.g., work on the Bengal Fan by Yokoyama et al., 1987) and will help in determining the role of erosion in the exhumation of the Dabie Shan coesite.

As a part of the discussion on the role and scale of erosion, and in support of their interpretation, Nie et al. (1994) noted that the quantity of the eroded material in the Songpan-Ganzi flysch is comparable to that of the Bengal Fan. Yet, the Bengal Fan is a good example which shows that a huge amount of erosion does not guarantee deep exhumation and exposure of high-pressure metamorphic rocks. Because high-pressure metamorphic rocks are rarely exposed in the Himalayas (Barnicoat and Treloar, 1989), the example of the Bengal Fan indicates the opposite.

It is likely that the unusual vertical motion inferred from the emergence of the Dabie Shan and other coesite-bearing terranes represents a unique (but not exotic) geodynamic process. Previous works on the structure of coesite-bearing terranes showed that major parts of the overburden were tectonically excised and that coesite-bearing units (as in many other blueschist terranes; Platt 1986) are delimited from above by tectonic contacts that cut out sections (Andersen et al., 1991; Avigad, 1992). This led workers to propose that extensional tectonics, perhaps triggered by gravitational instability (Andersen et al., 1991), helped unroof the coesite. In view of the scale of the tectonic burial of supracrustal rocks in the Dabie Shan, Nie et al. (1994) suggested that a Tibet-type mountain range existed in the Dabie Shan area in Triassic time. Although Nie et al. (1994) did not consider the potential of the Dabie Shan range to collapse, there are strong indications in favor of extensional reworking of the Dabie Shan orogenic wedge (Okay et al., 1993). One spectacular example is a 15 kbar metamorphic-discontinuity at the base of a low-temperature eclogite unit directly above a high-temperature eclogite unit (Okay et al., 1993). This discontinuity shows that crust has been removed from within the orogenic wedge and suggests that the role of orogenic extension in the exhumation of the Dabie-Shan coesite should also be considered.

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REPLY

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We welcome Avigad's Comment because it gives us an opportunity to emphasize the main lines of evidence and add more recent results in support of our hypothesis that there is a direct link between two of the most puzzling geologic features of China: (1) the regional exposure of ultra–high-pressure metamorphic rocks in the Dabie Shan and Sulu regions and (2) the largest accumulation of Triassic rocks on Earth in the Songpan-Ganzi (Nie et al., 1994). Avigad's objections can be summarized as follows: (1) There are no high-grade metamorphic rocks or minerals reported from the Songpan-Ganzi Triassic rocks; (2) "a huge amount of erosion does not guarantee deep exhumation and exposure of high-pressure metamorphic rocks" (Avigad, Comment above). In particular, the large amount of sediments in the Bengal Fan, coupled with the rarity of high-pressure metamorphic rocks from the Himalayas, "indicates the opposite" (Avigad, Comment), and (3) the role of extensional denudation and orogenic collapse should be given more consideration.

The presence or absence of high-grade metamorphic minerals in the Songpan-Ganzi flysch sequence would provide a direct test to our hypothesis, which has been the subject of joint projects between University of California (Los Angeles) and Stanford University geologists since this hypothesis was proposed independently by Nie et al. (1993) and Zhou and Graham (1993). Although we do not yet have these data, preliminary results from paleocurrent directions and provenance analysis of the Songpan-Ganzi Triassic flysch by Zhou and Graham (1993, 1995) point to a northeastern metamorphic source terrain, consistent with our hypothesis.

The purpose of comparing the Triassic Songpan-Ganzi flysch with the Tertiary Bengal Fan (Nie et al., 1994) is to highlight the extreme nature of the two sedimentary systems for their sheer volume, rather than to imply or "to guarantee deep exhumation and exposure of high-pressure metamorphic rocks" for other similar systems. The accumulation of these sediments, the formation of the Tibetan plateau and the Himalayas, and the exposure of ultra–high-pressure metamorphic assemblages are all rare geologic events that demand analysis on a case-by-case basis. For the same reason, we cannot agree with Avigad's statement, "Because high-pressure metamorphic rocks are rarely exposed in the Himalayas . . . the example of the Bengal Fan indicates the opposite." We raise two points in this regard. (1) It must be kept in mind that while the exhumation of the Dabie-Sulu ultra–high-pressure rocks occurred about 190 Ma (Nie et al., 1994), the unroofing of the Himalayas and the Tibetan plateau is an ongoing process. The apparent lack of ultra–high-pressure rock exposures in the Himalayas today does not guarantee that they will not be exposed in the future. (2) The size of the Triassic Dabie-Sulu collisional zone between north and south China is about one order of magnitude smaller than the Himalayas–Tibetan plateau. If a similar volume of sediment has been generated by erosion, the Dabie-Sulu zone would have been eroded to a much deeper structural level.

There are two fundamental arguments against extension playing a dominant role in the exhumation of the Dabie-Sulu ultra–high-pressure rocks. First, earlier and ongoing field observations within the ultra–high-pressure terrain in Dabie Shan (Okay and Şengör, 1992; Rowley et al., 1994; Hacker et al., 1995) indicate that east-west–striking, south-dipping syn– and post–ultra-high-pressure structures, as well as syn–retrograde amphibole facies overprint are all contractional. Second, as discussed in detail in Rowley (1995), the foreshortening of the metamorphic gradient observed in southern Dabie Shan and the close proximity (<60 km) of the Dabie ultra–high-pressure metamorphic rocks to the unmetamorphosed Triassic and Jurassic rocks along the northern margin of south China suggest that erosional removal of material from the southern front of Dabie Shan must have occurred synkinematically with the ultra–high-pressure rock being carried up by thrust faults.

In short, though our hypothesis remains to be proven, the three main lines of reasoning for it continue to be valid: (1) the timing of the exhumation of the Dabie-Sulu ultra–high-pressure metamorphic rocks agrees with that of accumulation of the massive Songpan-Ganzi flysch in the Late Triassic; (2) the volume of the Songpan-Ganzi flysch is similar to the volume of denudation required for the overlying rocks in the Dabie Shan to expose the ultra–high-pressure minerals; and (3) there is not another major clastic source to the west, south, and north to account for the Songpan-Ganzi flysch (Nie et al., 1994).

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