Discussion of "Role of the River Shear zone, Yunnan and Vietnam, in the continental extrusion of SE Asia" by M. Searle.

P.H. Leloup[1], P. Tapponnier[2], R. Lacassin[2]

[1] Université de Lyon, Lyon, F-69003, France ; université Lyon 1, Lyon, F-69003, France ; Ecole normale supérieure de Lyon, Lyon, F-69634, France ; CNRS, UMR 5570, Laboratoire des sciences de la terre, Villeurbanne, F-69622, France.
[2]Tectonique et Mécanique de la Lithosphère, Institut de Physique du Globe de Paris, and Université Paris 7, CNRS, Paris, France.

In his recent paper, M. Searle (2006) acknowledges that the 1000 km-long Ailao Shan – Red River shear zone (ASRR) is a large Miocene left-lateral shear zone, but speculates that left-lateral slip started after 21 Ma and claims that the total finite offset remains unknown. From this he concludes that continental extrusion was only a relatively minor tectonic factor during the India-Asia collision, as long argued by other authors (e.g., England & Houseman, 1986; Cobbold & Davy, 1988; Dewey et al., 1989; Houseman & England, 1993). We summarize below the field and geochronological evidence that makes us maintain a viewpoint in better accordance with facts.

Timing of left-lateral shear along the ASRR.

The ASRR is composed mostly of high-grade metamorphic rocks and deformed granitoids with ubiquitous evidence for left-lateral shear parallel to the belt (e.g., Tapponnier et al. 1986, 1990; Leloup et al. 1993, 1995, 2001). The crystallization of the granitoids has been dated between 22 and 35 Ma (Fig. 1d, e, f), (e.g. Schärer et al. 1990, 1994; Zhang & Schärer 1999) leading these authors to propose that left-lateral shear started at least ~35 Ma ago. In contrast, Searle (2006) claims that all the deformed granitoids found within the shear zone *predate* left-lateral shear and that their crystallization ages should thus be interpreted to provide an upper limit for the onset of deformation, rather than a lower limit, thus suggesting a maximum age of 21 Ma for this deformation. A clear understanding of the P-T history and *in situ* deformation history of the intrusions, as well as of their relationships with surrounding paragneisses, are fundamental for interpreting correctly the geochronological data.

That left-lateral shear in the Ailao Shan and the Diancang Shan took place at high temperatures is documented by left-laterally sheared garnet-sillimanite grade mylonitic paragneiss (Fig. 2e) (e.g. Leloup & Kienast, 1993; Leloup et al. 1995). Structural relationships show that garnet rims were in equilibrium with the matrix, with some garnets showing rolling structures (Fig. 2e), an inescapable proof of continuous growth during left-lateral shear. In the Ailao Shan in particular, P-T conditions were 615 - 780°C, and 3 - 8 Kb in garnet cores, while they were 580 - 780°C, and 3 - 6 Kb within their rims (Leloup & Kienast, 1993; Gilley et al. 2003). Such conditions are close to the granitic solidus, consistent with the presence of leucocratic melts interlayered within the paragneiss (Fig. 2e) and the occurrence of left-laterally sheared migmatitic paragneiss (Fig. 2f). The activation of the prismatic <C> glide system in quartz (Leloup & Kienast, 1993; Leloup et al. 1995) is also diagnostic of shearing temperatures close to the granitic solidus (e.g., Gapais and Barbarin, 1986). This is clearly in contradiction with M. Searle's assertion that all left-lateral kinematic indicators are low temperature fabrics.

In both the Ailao Shan and Diancang Shan ranges, high temperature left-lateral shear has been shown to be coeval with the intrusion of leucocratic dykes (Fig. 2), (Leloup & Kienast 1993; Lacassin et al. 1993; Schärer et al. 1994; Leloup et al. 1995). On several outcrops, sets of left-laterally sheared leucocratic dykes are consistently crosscut by less deformed ones. Synkinematic melt emplacement in the mylonites is also indicated by leucosomes that fill gaps between boudins, with tailing at the extremity of such structures and localization along left-lateral shear planes (Leloup et al., 1995) (Figs. 2a, c). First published U/Pb ages of the leucocratic dykes range between 22.4 ± 0.2 and 24.1 ± 0.2 Ma in the Ailao Shan, and between 22.4 ± 0.2 and 24.7 ± 0.2 Ma in the Diancang Shan (Fig. 1d) (Schärer et al. 1990, 1994; Zhang & Schärer 1999). Since the sampled dykes were the widest ones, hence usually the less stretched and deformed, they provide minimum ages of the deformation. Recently cored samples of five dykes from site C1 in the Ailao Shan have provided new ages. The two most deformed dykes are ~ 30 Ma old, while the less deformed one is ~22 Ma and the intermediately deformed ones have ages of 24 and 26 Ma (Th/Pb ages on monazite, Fig. 1d, Fig.2d) (Sassier et al., 2006). This shows that left-lateral shear started in this outcrop prior to 26 Ma at the very least. Since the most deformed dykes cross-cut orthogneiss with evidence for penetrative HT left-lateral shear (Fig. 2g), the minimum age for the onset of left-lateral shearing is in fact ~30 Ma at this locality.

The age of high-temperature metamorphism associated with left-lateral shear is also constrained by U-Th/Pb dating of monazites (Gilley et al. 2003). In the Xuelong Shan, Diancang Shan and Ailao Shan ranges, 47 of the 50 ages of matrix monazite from 10 different samples are between 19 and 34.5 Ma (Fig. 1b), demonstrating that high-temperature metamorphism lasted ~16 Myr. This is confirmed by ages of monazite inclusions within garnets from the Ailao Shan (16 ages in 6 different samples) that span the period between 21.5 and 34.5 Ma (Fig. 1b) (Gilley et al. 2003). The matrix and garnet inclusion monazites display the same age range and inclusion and matrix ages overlap in each sample. This could hardly be the case if a hypothetical, early-metamorphic event had been preserved within the garnet cores.

Monazites give a broader U-Th/Pb age pattern in the Daynuiconvoi range, from 21 to 208 Ma, and 43 to 224 Ma for matrix and inclusion monazites, respectively (Fig. 1c), showing that these rocks experienced a poly-metamorphic history (Gilley et al. 2003). The oldest ages likely correspond to the Indosinian (250-160 Ma) metamorphism and subsequent cooling documented in the nearby SongChay dome (Roger et al. 2000; Maluski et al. 2001; Gilley et al. 2003) and elsewhere in Indochina (e.g. Carter et al. 2002). However, matrix monazites show a clear age peak between 21.5 and 32.5 Ma (12 data from 5 different samples), similar to the age range from the Ailao Shan, Diancang Shan and Xuelong Shan ranges, implying partial resetting of an Indosinian metamorphic assemblage during Oligo-Miocene deformation (Gilley et al. 2003).

After peak temperatures, left-lateral shear continued during cooling below 600°C until greenschist conditions were reached (Leloup et al. 1993, 1995, 2001; Harrison et al. 1992, 1996; Jolivet, 2001; Nam, 1998). Because $^{39}Ar/^{40}Ar$ ages generally reflect cooling below a closure temperature (from ~510 ± 50°C for amphiboles to < 200°C for the less retentive domains of K-feldspars), the cooling and exhumation can be dated, yielding further indirect constraints on the timing of shearing. Of the sixty-eight published $^{39}Ar/^{40}Ar$ amphibole and mica ages from the Ailao Shan – Red River shear zone, only three give ages older than 35 Ma, but 59 are older than 21 Ma (Harrison et al. 1992, 1996; Leloup et al. 1993, 2001; Wang et al., 1998, 2000; Maluski et al. 2001; Garnier et al. 2002). All 52 K-feldspar show ages younger than 25 Ma for their less retentive domains (with 28 ≤21Ma), and only two show ages older than 35 Ma for their more retentive domains (Harrisson et al. 1992, 1996; Leloup et al. 1993, 2001; Wang et al. 1998, 2000). Most of these data are summarized in Leloup et al. (2001, plate 2 and Table 7). These data show that parts of the shear zone started to cool as soon as ~35 Ma, and that the temperature had dropped below ~250°C before 21 Ma in the Xuelong Shan, the southern half of the Ailao Shan, the FanSiPang and the Daynuiconvoy ranges. If deformation had started at 21 Ma, there should not be any evidence for left-lateral ductile deformation in any of these ranges, which is not the case.

A more detailed analysis shows that different parts of the Ailao Shan - Red River shear zone have distinct cooling histories (Leloup et al. 2001). An early cooling phase (0 on Fig. 1a) occurred soon after 35 Ma in the FanSiPang and LoGam ranges in Vietnam, while the main phase of rapid cooling (I on Fig. 1a) lasted from 30 to ~28 Ma in the Xuelong Shan range, from 23 to 20 Ma in the Diancang Shan, and from 27 to 23 Ma in the Daynuiconvoi. In the Ailao Shan range, this phase was diachronous along strike, lasting from ~28 to 25 Ma in the northwest, and 21 to 17 Ma in the southeast. This pattern led Harrison et al. (1996) and Leloup et al. (2001a) to propose a "zipper" kinematic model linking strike-slip tectonics and exhumation. This offers a simple explanation for the cooling pattern and yields an estimate of the left-lateral slip-rate along the ASRR, which is compatible with the total offset and life-span of the shear zone and with quantitative seafloor-spreading kinematics in the South China Sea (Briais et al., 1993).

When combined with structural work, the available geochronological data summarized in Fig. 1 thus leave no doubt that left-lateral shear started at least around 35 Ma and lasted until ~17 Ma. The proposal that the onset of shear did not occur until ~27 Ma (Wang et al. 2001) is in contradiction with the cooling histories and structural data from both the Xuelong Shan and FanSiPang ranges, and with the ages of the oldest synkinematic leucocratic dykes and metamorphic monazites elsewhere. An onset of deformation after ~21 Ma (Searle 2006) is in contradiction with cooling histories in all ranges except the Diancang Shan and the North part of the Ailao Shan, as well as with the ages of the all synkinematic leucocratic dykes and metamorphic monazites.

Finite offsets across the Ailao Shan – Red River shear zone.

Searle (2006) states that "none of the features cited by Leloup et al. (1995) are reliable markers, and the finite geological offsets along the Red-River remain unknown". While there is no question that the ASRR shear zone is not the small-scale type of brittle fault across which structural geologists have long been used to linking piercing points, there is compelling evidence for a total offset larger than 500 km (e.g., Leloup et al., 1995; Chung et al. 1997; Leloup et al., 2001), and we recall here briefly the most important points of our argument.

It has been recognized for over 40 years (e.g. Huang 1960) that regional geological features cannot be matched simply across the Ailao Shan – Red River shear zone. Depending on the feature considered, large-scale apparent left-lateral offsets vary between >400 km to 1050 ± 100 (e.g., Tapponnier et al. 1986; Leloup et al. 1995; Chung et al. 1997). Searle (2006) contests the ≥650 km offset between the Nan-Uttaradit suture south of the fault with the Jinsha – Benzilan north of it. Because ultramafic slivers have been mapped southwest (not northwest as mentioned by Searle) of the Ailao Shan (Leloup et al. 1995), he instead proposes that the Song Ma suture has to be matched with the Jinsha and that "the Red River shear zone may follow the suture for part of its course in South Yunnan". This is partly incorrect because the Ailao Shan ultramafic rocks are strongly affected by left lateral shear (Leloup et al. 1995) and correspond to smeared pieces of a suture zone cut by the Ailao Shan-Red River shear zone, while the Song Ma crops out 120 km south of the main shear zone in north Vietnam. The Ailao Shan-Red River shear zone did not follow a pre-existing suture, but instead the Jinsha suture has been partly drawn into parallelism with it because of intense deformation. Furthermore, matching the Song Ma suture, instead of the Nan-Uttaradit, with the Jinsha suture would also imply an offset ≥ 650 km.

The 40–29 Ma ultra-potassic igneous rocks that outcrop in Tibet north of the Ailao Shan-Red River shear zone, along the structure itself (<20 km from the gneissic core) and farther south in Vietnam (Wang et al. 2001, Guo et al. 2005; Chung et al. 1998) define an apparent sinistral offset of ~600 km between the JianChuan and FanSiPan magmatic provinces corresponding to motion younger than ~35 Ma (e.g. Chung et al. 1997). This distance is only a lower bound of the total offset on the shear zone because a larger motion (~680 km) is needed to match the eastern boundaries of the two magmatic provinces.

Numerous palaeomagnetic studies, none of which are cited by Searle (2006), are consistent with clockwise rotation and 10 ± 3° of southward motion of Indochina with respect to South China since the Upper Cretaceous (see Leloup et al. 2001a and references therein). If the strike of the shear zone is assumed to have remained constant, this corresponds to 1400 ± 400 km of left-lateral displacement. A clockwise rotation of the fault zone would imply an even larger offset.

In any case, the left-lateral offset at the end of left-lateral shear (~17 Ma) corresponds to the present-day apparent left-lateral offset augmented by the amount of later right-lateral offset along the Red River fault, which has been estimated to be between 6 and 57 km (Allen et al. 1984; Leloup et al. 1995; Replumaz et al. 2001; Schoenbohm et al. 2006).

Conclusions

The inference of an initiation of the ASRR shear zone at 21Ma does not hold in front of the geological and geochronological data. A large number of independent data sets, including geological offsets, structural, petrological and geochronological studies within the shear zone, palaeomagnetic measurements in South China and Indochina, magnetic anomalies in the South China Sea (Briais et al. 1993), and the timing of sedimentation and tectonic style in the YinGeHai pull-apart basin (Clift & Sun 2006), are consistent with our view that the Ailao Shan-Red River shear zone had a left-lateral sense of movement between ~34 Ma and ~17 Ma, a total finite offset larger than 500 km and slip rates of the order of 3 to 5 cm/yr.

The Ailao Shan-Red River shear zone and its timing are keys to debates on the rheology of the continental lithosphere in general and the nature of the India-Eurasia collision in particular. Large-scale Oligo-Miocene left-lateral motion along the Ailao Shan-Red River shear zone and Mio-Pliocene reversal to right-lateral faulting along the Red-River fault can be explained neither by continuous deformation steadily accumulating in front of India (e.g., England & Houseman 1986; Houseman & England, 1993), right-lateral shear along Tibet's eastern margin (e.g., Cobbold & Davy 1988; Dewey et al. 1989), nor lower crustal outflow away from Tibet.

Figures caption:

Fig. 1 Synthesis of the geochronological data on the ASRR compared to the timing proposed for left-lateral slip. See text for details. **a)** Main cooling events in each range of the ASRR from Ar/Ar and FT. Note that temperature dropped below 250°C after cooling phases 0 and 1 in all ranges unless Diancang Shan (Leloup et al., 2001). **b to f)**. Cumulative probability plots of Th/Pb ages. Left column with all data, right column restricted to data from 0 to 70 Ma. **b)** Xuelong Shan, Diancan Shan and Ailao Shan monazite ages (Gilley et al., 2003). **c)** Daynuiconvoy monazite ages (Gilley et al., 2003). **d)** Xuelong Shan, Diancan Shan and Ailao Shan U/Pb ages of leucocratic dykes (Schärer et al., 1990; 1994; Zhang and Schärer, 1999; Sassier et al., 2006). **e)** Ailao Shan U/Pb ages of orthogneiss (Schärer et al., 1994; Zhang and Schärer, 1999). **f)** Ultra-potassic igneous rocks along the ASRR (Wang et al. 2001; Chung et al. 1998). **g)** Timing of SCS sea floor spreading (Briais et al., 1993 modified according to Cande and Kent, 1995) and time interval proposed for left-lateral and right-lateral shear along the ASRR.

Fig. 2 Field evidence for leucocratic melts and high-temperatures synkinematic to the left-lateral deformation.

a) Syn-left-lateral shear leucocratic dykes. 1 to 3 from older to younger. Fig. 12a of Leloup et al (1993) modified. **b)** Several generations of syn-left-lateral shear leucocratic dykes. Deformation and age decreasing with increasing numbers. Fig. 12b of Leloup et al (1993) modified. **c)** Sketch of boudinated amphibolitc layers with leucocratic melts (stippled pattern) From Fig. 14e of Leloup et al. (1995). **d)** Oblique view of outcrop C1 showing several generations of leucocratic dykes, some of which have been dated (Sassier et al., 2006). Less deformed, intermediate, and more deformed dykes appear respectively in purple, yellow and orange. **e)** Garnets synkinematic to the left-lateral deformation. Top : helicitic garnet, polished rock slab. Bottom : garnet in migmatitic paragneiss, view from above. **f)** Migmatitic paragneiss with left-lateral shear planes. Fig. 15b of Leloup et al., 1995. View from above. **g)** High-temperature orthogneiss with melted patches around the δ and σ type feldspars. Fig. 16a of Leloup et al. (1995) modified. View from above.

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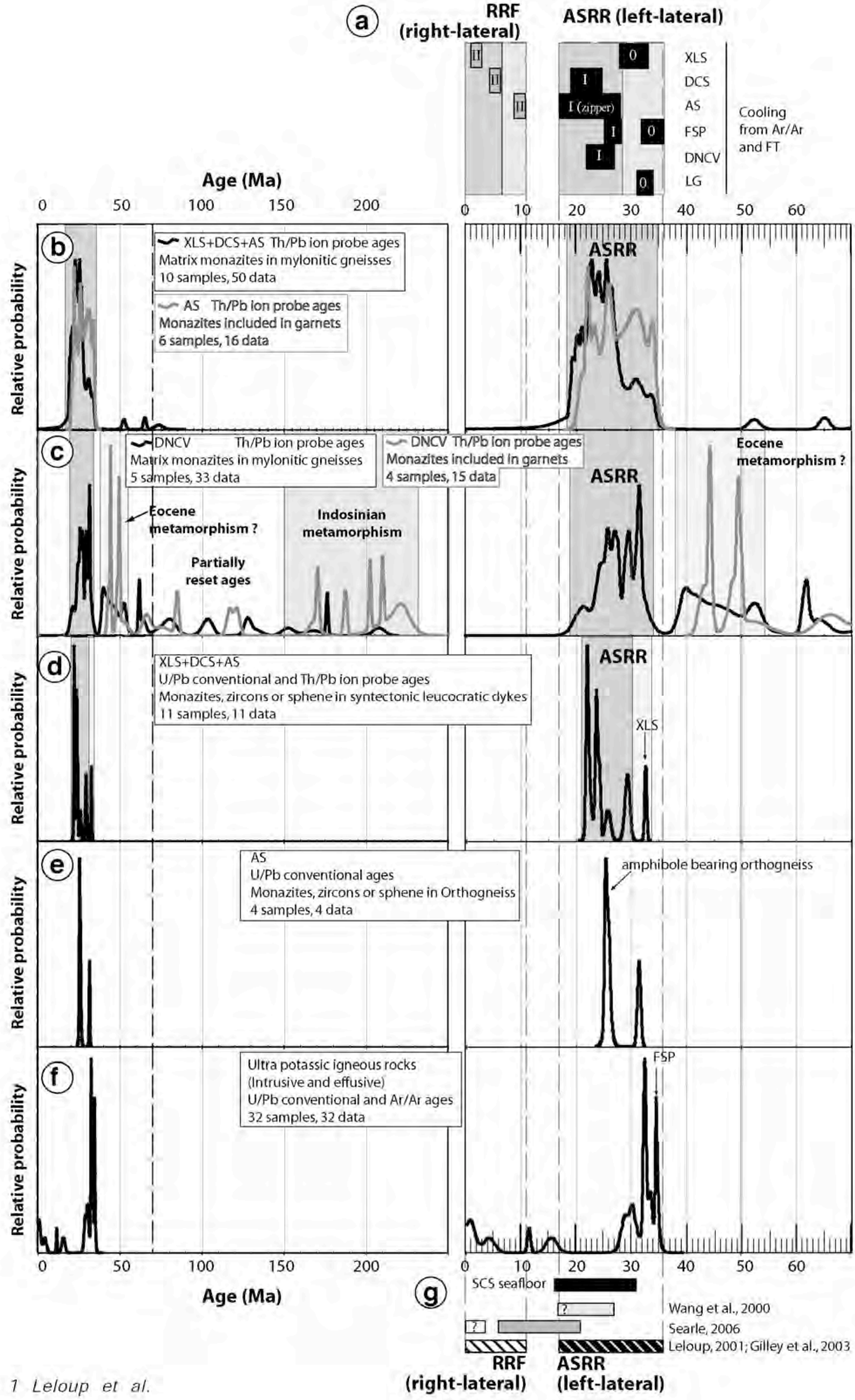

Fig. 1 Leloup et al.

Fig. 2 Leloup et al.