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Typology of detrital zircon as a key to unravelling provenance in rift siliciclastic sequences (Permo-Carboniferous of Spiti, N India)

Typologie des zircons détritiques pour déterminer la provenance des séquences sédimentaires de rift (Permo-Carbonifère de Spiti, Inde du Nord)

Valeria CAIRONI *, Eduardo GARZANTI *,** and Dario SCIUNNACH *

ABSTRACT. – Detrital zircon populations from Carboniferous to Permian sandstones from the Lozar Section of Spiti, northern India, were analyzed with the typology method in order to obtain complementary information on the source areas of the sediments. Zircon grains were subdivided into several groups and subgroups, according to degree of abrasion and morphological features.

First appearance of detrital zircons with distinct typologic signature within successive stratigraphic intervals provided useful data about the tectono-magmatic evolution of the northern Indian margin during Late Paleozoic rifting of Gondwana and initial opening of Neotethys. The base of the studied sequence (Lower Carboniferous Thabo Fm.) is characterized by a largely cratonic provenance, seemingly from the Indian Shield to the South. In the Upper Carboniferous Chichong Fm., first occurrence of typical zircons from anatectic granites and increasing abundance of granitoid detritus suggest rapid uplift and unroofing of anatectic rocks of probable Cambro-Ordovician age. In the lowermost Permian (Asselian) glaciomarine Ganmachidam Diamictite, euhedral detrital zircons with peculiar features, associated with Cr-rich chromian spinels and mafic to felsic volcanic rock fragments, hint at emplacement of bimodal alkaline magmatic suites. The same sources, possibly including subvolcanic bodies, continued to be eroded until final break-up, documented by the Permian Kuling Group.

Keywords : Detrital Zircon, Typology Method, Sandstones, Spiti District, Northern India.

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RÉSUMÉ. – La typologie de population de zircons détritiques dans les grès permiens et carbonifères de la coupe de Lozar (Vallée de la Spiti, au nord de l'Inde) a été analysée pour mieux définir les régions sources de ces zircons. Les zircons sont séparés en plusieurs groupes et sous-groupes, selon leur degré d'abrasion et leurs caractères morphologiques. La première arrivée de zircons avec une signature typologique distincte permet de préciser l'évolution tectono-magmatique de la marge indienne nord au cours du rifting puis de l'ouverture de Néo-Téthys aux dépens de Gondwana, au Paléozoïque supérieur. La base de la séquence étudiée (Formation Thabo, Carbonifère inférieur) est caractérisée par une provenance essentiellement cratonique apparemment dérivée de l'Inde, au sud. Dans la formation Chichong, datée du Carbonifère supérieur, la première apparition de zircons typiques de granites dérivés de la fusion anatectique et l'abondance croissante de clastes granitiques suggèrent une érosion rapide et l'exhumation de roches anatectiques d'âge Cambro-Ordovicien probable. Au Permien inférieur (Asselien), dans les diamictites glaciomarines de Ganmachidam, des zircons automorphes particuliers, associés à des spinelles riches en chrome et à des clastes de roches volcaniques basiques et felsiques, révèlent l'existence d'un magmatisme bimodal. La même source, peut être incluant des corps sub-volcaniques, a continué à être érodée jusqu'à la fin de la fragmentation du Gondwana, documentée par le groupe permien de Kuling.

Mots-clés : Zircons détritiques, Typologie, grès, Spiti, Inde du Nord.

INTRODUCTION

The zircon typology method has been successfully used for some twenty years to discriminate the origin of felsic magmatic rocks. In the present work, this

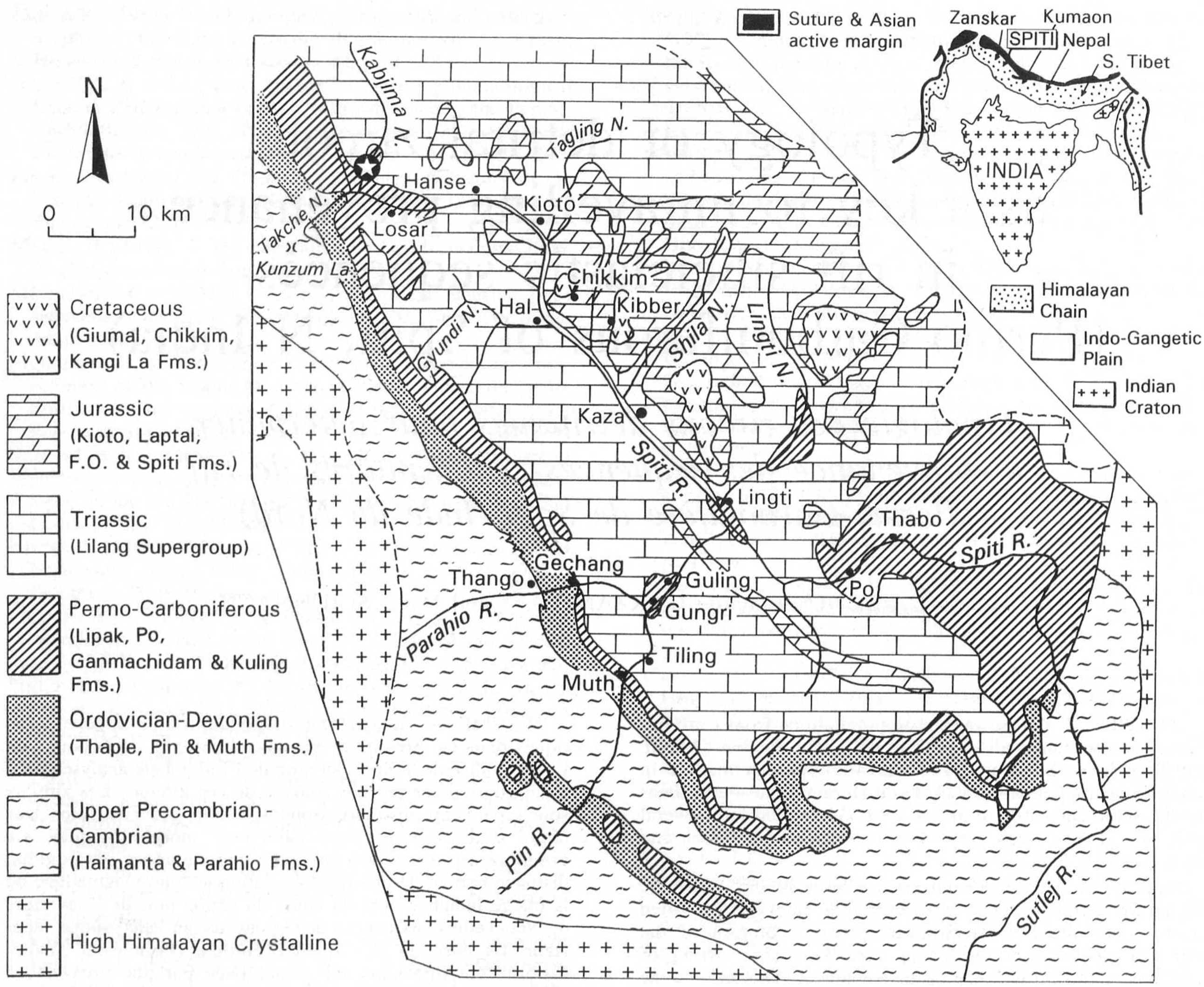


Fig. 1. – **Geological sketch map of the Spiti River Valley (after Bagati, 1990).** Star indicates the site where the studied samples were collected in measured stratigraphic sections.

Fig. 1. – ***Carte géologique schématique de la vallée de la Spiti (d'après Bagati, 1990).*** *Etoile = échantillons sur coupes stratigraphiques mesurées.*

technique is applied to investigate provenance of siliciclastic rocks from the classical area of the Spiti Tethys Himalaya (Zanskar-Spiti Synclinorium; Himachal Pradesh, northern India; fig. 1), where spectacular Upper Paleozoic sedimentary successions are exposed. Detailed stratigraphic sections, complete from the mid-Lower Carboniferous to the top of the Permian, were measured in the Losar area (both NE and SW of the Kabjima Nala), during the 1992 expedition carried out by the University of Milano with partial sponsorship of EV-K2-CNR. Fifty-two samples were collected for mineralogical and petrographical analyses.

THE PERMO-CARBONIFEROUS OF THE TETHYS HIMALAYA

The sedimentary succession of the Tethys Himalaya records the complex sequence of spectacular paleogeographic events which marked the paleotectonic evolution of the northern India continental margin in the Permo-Carboniferous, as the great Gondwanian glaciation and the active extensional tectonism with associated magmatism which led to initial opening of Neotethys. Owing to logistic difficulties in studying rock outcrops exposed at high altitudes, to intense tectonic deformation and to complex geometry and lateral variations of sedimentary units, only recently a reference stratigraphic framework for the Permo-Carboniferous sedimentary succession has become available, from the Spiti-Zanskar Synclinorium (Garzanti *et al.,* 1995a, b) to the Dolpo-Manang Synclinorium (central Nepal; Garzanti *et al.,* 1992; 1994).

Sedimentary succession

The Lipak platform carbonates and gypsum deposits are overlain by the Po Group, consisting of two sand-rich stratigraphic units mainly deposited in tide-dominated coastal settings, alternating with two fossiliferous black shale units accumulated in middle shelf environments (Thabo Formation, Fenestella Shale, Kabjima Quartzarenite and Chichong Formation).

Subarkoses, characterizing the Lipak Fm. and lower Thabo Fm. (Tournaisian/Early Visean), pass upward to exclusive quartzarenites in the middle-upper Thabo Fm. (Late Visean/Serpukhovian), Fenestella Shale (containing rich brachiopod associations of Bashkirian age) and Kabjima Quartzarenite. The Chichong Fm. marks a major tectonically-enhanced? transgressive event associated with a notable increase of detrital feldspars; rich chaetetid and brachiopod faunas hint at a Moscovian age for the "Chaetetid beds", which in the upper part display varve-like lamination and scattered pebbles suggesting glacially-influenced deposition. The Chichong Fm. is capped by a glacio-fluvial? cobble conglomerate horizon ("Pebbly beds"), suggesting close relationships between onset of the Gondwanian glaciation and start of rapid tectonic uplift.

The overlying Ganmachidam Diamictite, deposited in glacio-marine environments, is characterized by a wealth of sedimentary detritus, documenting an active stage of basin inversion and progressive erosion of Paleozoic sedimentary successions. Bimodal (felsic to mafic) volcanic detritus typical of rift settings begins already at the base ("Basal diamictite"), whereas plutonic detritus becomes significant and chromian spinel was found in the middle part ("Middle diamictite"), which locally contains the classical gondwanian cold-water faunas of Asselian age (Garzanti *et al.,* 1995a). The Ganmachidam Fm. may document an unroofing sequence, since detritus in its upper part ("Lithic microconglomerates" and "Upper diamictite") was derived from progressively older sedimentary successions including Cambrian/Precambrian rocks; volcanic and plutonic detritus reach a maximum at the top of the unit ("Upper diamictite").

The Ganmachidam Diamictite is unconformably overlain by the Kuling Group, which consists of coastal pebbly hybrid arenites with dominant spiriferids of Late Sakmarian-Midian age (Gechang Formation), overlain by shelf, black phosphatic shales rich in productids of Djulfian age (Gungri Formation). The Gungri Fm., capping the Paleozoic succession in the whole Zanskar-Spiti Synclinorium, was deposited in warm climates during major widespread transgression and documents rapid thermal subsidence of the Indian passive continental margin facing the newly-opened Neotethys Ocean.

Magmatic rocks

The Paleozoic succession of the NW Tethys Himalaya contains injected dykes and intercalated lavas emplaced during the initial stages of rifting and incipient oceanization of Neotethys.

Swarms of basaltic dykes of alkaline to tholeiitic affinity, each 1 to 20 m wide, cross-cut Upper Precambrian to Lower Carboniferous units of the Spiti-Zanskar Synclinorium (particularly extensive in the Baralacha La-Tanze area; Gaetani *et al.,* 1986, p.455; Garzanti *et al.,* 1986, fig. 4; Vannay & Spring, 1993) and are also found within the High Himalayan Crystalline as far as NE Pakistan (Papritz & Rey, 1989). For their geochemical characters, these dykes were considered either as similar and comagmatic with the mid-Permian Panjal Traps (Honegger in Gaetani *et al.,* 1986, table I; Papritz & Rey, 1989) or representing a distinct event related to earlier rifting stages (Vannay, 1993; Vannay & Spring, 1993).

Also, porphyric granitic dykes up to 15-20 m thick locally cut the Paleozoic Tethys Himalaya succession in easternmost Zanskar (Raina & Bhattacharyya, 1977; Kanwar & Bhandari, 1979). These alkaline felsic rocks are dated at 284±1 Ma (Yunam granite of Spring *et al.,* 1993) and thus ascribed to the Early Permian (Asselian according to the time scale of Harland *et al.,* 1989). Early rifting alkaline activity is also documented by nepheline syenites in Northern Pakistan, dated at 315 to 297 Ma (Le Bas *et al.,* 1987).

A huge volcanic event is next recorded by the Panjal Traps in the late Early Permian (Artinskian-Bolorian; Srikantia & Bhargava, 1983; Garzanti *et al.,* 1995b). These tholeiitic to mildly alkaline continental flood basalts reach a thickness of 2500 m in Kashmir and are found today in an area more than 10^5 km^2 wide, from easternmost Zanskar to NE Pakistan (Honegger *et al.,* 1982; Nakazawa & Dickins, 1985; Papritz & Rey, 1989).

METHODS

Heavy minerals concentration

Twelve selected sandstone samples, cemented with less than 10% of quartzose overgrowths and displaying several heavy minerals in thin section, were mechanically crushed into granules about 5 mm in diameter. Light particles less than 4 Φ in diameter were siphoned off (withdrawal at depth of 8 cm, 26 seconds after stirring). Successive treatments with hydrochloric acid (37%), sodium carbonate in sonic tank and warm oxalic acid were each followed by washing in hydrogen peroxide and siphoning. From the resulting sand fraction, passed through a 250 μm-mesh sieve, heavy minerals were separated by means of bromoform (density = 2.84 kg/l) and mounted on glass slides with Canada balsam. Since zircon is the most common mineral in the studied ultrastable suite, no specific separation of zircons from other heavy minerals has been necessary.

Zircon typology method

Zircon is an ubiquitous heavy mineral in sediments, due to its hardness, lack of good cleavage and resistance to chemical corrosion (Blatt *et al.*, 1980). After a single sedimentary cycle, zircon morphology is generally preserved relatively well, and its crystalline forms may be commonly recognized. Since zircon morphology correlates statistically with the physico-chemical conditions characterizing the environment where it first crystallized (Pupin, 1976, 1980), typologic analysis of detrital zircons may give significant complementary information on source rocks and also represents an interesting correlation tool in provenance studies. This possibility is based on the assumption that diagenetic processes have negligible effects on the morphology of crystals, as seems to be demonstrated by several authors (Poldervaart, 1955; Hoppe, 1962; Hoppe *et al.*, 1965; Marshall, 1967; Pupin 1976; Alinat *et al.*, 1979).

In the typology method (Pupin & Turco, 1972a), zircon populations obtained by routine concentration procedures are mounted between microscope slides with Canada balsam and analyzed under the microscope at 250 × magnification. Morphological types and subtypes are defined according to occurrence and relative development of crystalline forms most sensitive to physico-chemical conditions of the environment. The main factors proposed as controlling the typologic variations are: for the bipyramids, the relative contents of Al vs alkalies (Pupin, 1976); for the prisms, temperature and fluid pressure (Pupin & Turco, 1972b; Pupin *et al.*, 1978), the degree of zircon supersaturation in the liquid (Vavra, 1990) and the concentration of some trace elements relative to Zr (Benisek & Finger, 1993). The main subtypes are arranged in a "typologic grid" (fig. 2) and each of them is identified by a couple of empirical coordinates A, T; supplementary bipyramidal forms define secondary subtypes, which are grouped together with the corresponding main subtype of the grid. A mean point of A, $\bar{T}$ coordinates is calculated from the frequency of the different subtypes in the studied population. For primary magmatic populations, position of the mean points on the I. A / I. T diagram (called "typologic evolution diagram") varies according to the petrochemical characters of the rock, allowing to define several typical fields (Pupin, 1980, 1985). Other morphological features (e.g., colour, overgrowths, cores, inclusions) which characterize zircons from different rock types are also taken into account.

Application of the typology method to the study of detrital zircon in sediments presents additional difficulties. Since a single detrital population is derived from a

I.T \ I.A	100	200	300	400	500	600	700	800	prism ⇓
100	B	AB1	AB2	AB3	AB4	AB5	A	C	0
200	H	L1	L2	L3	L4	L5	G1-3	I	110
300	Q1	S1	S2	S3	S4	S5	P1	R1	110>>
400	Q2	S6	S7	S8	S9	S10	P2	R2	110>
500	Q3	S11	S12	S13	S14	S15	P3	R3	110=
600	Q4	S16	S17	S18	S19	S20	P4	R4	100>
700	Q5	S21	S22	S23	S24	S25	P5	R5	100>>
800	E	J1	J2	J3	J4	J5	D	F	100
bipyramid ⇒	211	211>>	211>	211=	101>	101>>	101	301	

Fig.2. – **Classification of the main types and subtypes of zircon crystals in the typologic grid (Pupin, 1976).** Bipyramidal faces vary along the A axis (horizontal); prism faces along the T axis (vertical). Face indices after the structural orientation.

Fig. 2. – ***Classification des principaux types et sous-types de zircons (grille typologique de Pupin, 1976).*** *Les faces bipyramidales varient le long de l'axe A (abscisse) et les faces prismatiques le long de l'axe T (ordonnées). Indices des formes selon l'orientation structurale.*

variety of heterogeneous source rocks, zircon grains have to be somehow arbitrarily grouped in distinct clusters, each supposedly reflecting a homogeneous source. The first objective criterium is the degree of abrasion: crystals showing only slightly pitted faces and smoothed or irregularly broken edges and corners are held to be "first cycle" grains, and are therefore separated from rounded and abraded zircons (probably "recycled" grains). Abraded zircons, however, may also represent first cycle grains which owe their higher degree of abrasion to more prolonged transport or to higher-energy processes (Winter, 1984), or even to higher sensitivity to abrasion or chemical corrosion (e.g., partly metamict grains). If this is the case, a skewed representation of the original population will be obtained, since only the less abraded crystals can be typologically determined. Another problem concerning the correct attribution of each crystal to the proper group is the possible convergence of characters between zircons of different origins (i.e., overlapping fields on the typologic evolution diagram).

Further problems are found when the method is applied to ancient sedimentary rocks, since the parent rocks are unknown. Reliability of the results is thus largely dependent on the carefulness and objectiveness

Table I. – **Main features and proposed provenance of recognized zircon groups and subgroups.**
Tableau I. – ***Principaux traits et provenance proposée des groupes et sous-groupes de zircons.***

GROUP	EDGES CORNERS	FACES	INCLUSIONS	ZONING	CORES	OVERGROWTHS	COLOUR	PROPOSED PROVENANCE
A	slightly abraded	clean to slightly pitted	Ap, various crystals	some	no	some coloured	colourless, pale pink, brown	calcalkaline plutonites
A_1	slightly abraded	110, 211, 301 pitted	Ap, various crystals	rare	no	no	colourless, pale pink	calcalkaline plutonites
A_2	slightly abraded	mainly clean	coarse-grained Ap, dark globules	no	no	no	colourless	calcalkaline plutonites
A_3	slightly smoothed	clean	few	no	no	no	pale pink	charnockites
B	smoothed or slightly abraded	slightly pitted	dark microgranular	frequent	frequent	thick, zoned, coloured	brownish pink to brown	aluminous anatectic granites
C	slightly smoothed	clean to slightly pitted	rare bubbles or dust-like aggregates	rare	large corroded	colourless, no inclusions	colourless	migmatites
C_1	smoothed to rounded	clean	rare bubbles	rare	large corroded	colourless, no inclusions	colourless to pale pink	granulites
C_2	smoothed to rounded	clean	bubbles, small grains	rare	large corroded	coloured, no inclusions	pink, brownish pink	migmatites or granulites
D	sharp	clean	acicular Ap, opaques, glass	some eccentric	no	no	colourless	alkaline rhyolites
D_1	slightly smoothed	slightly pitted	acicular Ap, opaques	rare	no	no	pink to pale purple	alkaline rhyolites
E	abraded, rounded	pitted	variable	rare	rare	rare	variable	sandstones

with which detrital populations are separated; general geological information is better not used at this stage, since it might lead to circular confirmation of one's own prejudices.

In the present study, zircon grains from the Po Group and Ganmachidam Formation of Spiti were subdivided into 6 different groups and 6 subgroups, according to morphological features and degree of abrasion; their characteristics are summarized below (table I).

DATA

Populations of zircon morphotypes

Group A: subhedral crystals with slightly abraded edges and corners; clean to slightly pitted faces (fig. 3a, b). Grains are colourless or pale pink to brown; a few are markedly zoned (fig. 3b). Overgrowths are sometimes observed. Typical inclusions point to a magmatic origin (Pupin, 1976): zircons with well developed {100} faces

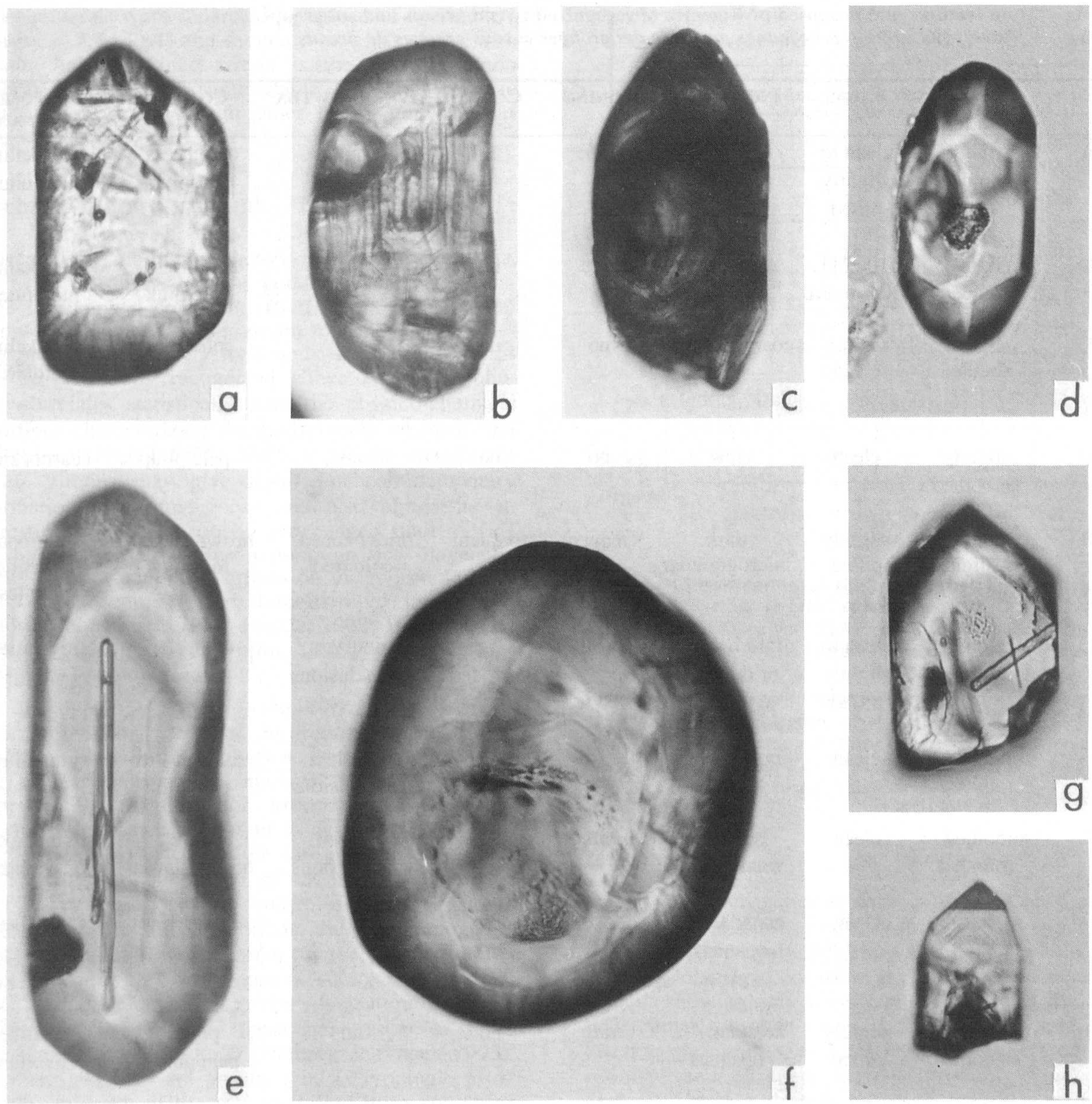


Fig.3. – **Different types of zircon crystals.** a, b : group A, subtypes U20, U19 (corresponding to S20, S19 + supplementary bipyramid {301}); c : group B, subtype S2; d : group C, subtype S3; e : subgroup A3, subtype U24 (S24 + {301}) + bipyramidal faces of high index; f : subgroup C1, undetermined typology; g, h : group D, subtypes J4, T14 (P5 + {301}).

Fig. 3 – ***Différents types de zircon.*** *a, b : groupe A, sous-types U20, U19 (correspondant à S20, S19 + la bipyramide {301}); c : groupe B, sous-type S2; d : groupe C, subtype S3; e : sous-groupe A3; sous-type U24 (S24 + {301}) + faces bipyramidées à fort indice; f : sous-groupe C1, typologie indéterminée; g, h : groupe D, sous-types J4, T14 (P5+{301}).*

mostly contain apatite prisms and high-relief rounded or polygonal crystals, whereas zircons with prevailing {110} faces mainly contain brown microgranular materials. Morphological characters and typologic distributions are compatible with first-cycle provenance from calcalkaline intrusive rocks or orthogneisses (Pupin, 1980).

Subgroup A1 is characterized by preferential abrasion on selected crystal faces: {110} prism faces; {211} and {301} bipyramidal faces. Typologies and secondary characters do not differ significantly from A crystals.

Subgroup A2 consists of clear and colourless crystals, with clean faces and only slightly irregular edges; they are characterized by peculiar inclusions: large dark globules and coarse short apatite prisms.

Subgroup A3 is represented by pale pink, transparent crystals, with no or few inclusions (acicular apatite, small dark crystals). These coarse-grained crystals display well developed {100} prism forms, supplementary bipyramidal faces of high indices and poorly developed bipyramidal terminations (fig. 3e).

Group B (fig. 3c): coloured crystals with smoothed edges and corners, commonly rich in dark, microgranular inclusions. Thick overgrowths, generally zoned, are frequent; inherited cores, more or less corroded, are observed in many crystals. Typologic characters, as well as occurrence of partly metamict crystals and of cores, suggest origin from aluminous granites of likely anatectic origin (Pupin, 1980).

Group C (fig. 3d): crystals with variably smoothed edges and corners, clean to slightly pitted faces. Typical inclusions (dust-like or aggregates of "bubbles", small rounded grains) frequently underline an inherited, corroded core. These characters are typical of zircons from anatectic migmatites (Pupin, 1976, 1994). Such crystals are indicated as "recrystallized", to stress that they acquired new morphological characters during high-grade metamorphism, probably due to partial resorption and / or overgrowth.

Subgroup C1 (fig. 3f) includes subovoidal to globular grains, with rounded edges and corners, low length / width ratio and few inclusions. Clean faces suggest that their rounded aspect is probably an original feature and is not due to abrasion during sedimentary transport.

Subgroup C2: typical features are pink or brownish pink colour and large cores with abundant microgranular inclusions. Typologic distribution, degree of abrasion and rounded shape recall C1 crystals.

Group D (fig. 3g, h): euhedral crystals with sharp edges and corners; faces are relatively clean. Grains are colourless and transparent; typical inclusions are elongated to acicular apatite prisms, opaques and glass? (irregularly-shaped inclusions). Channel-like cavities, commonly filled with acicular apatite or other inclusions, and lacks of growth, probably induced by adjacent minerals, are frequent. Such features are commonly observed in zircons from volcanic rocks and are considered an indication of rapid nucleation (Pupin, 1976). High T index typologies, as well as generally small average dimensions and low length / width ratio, are also consistent with provenance from volcanic rocks.

Subgroup D1: crystals with peculiar pink to pale purple colour; compared to group D zircons, they show slightly more corroded edges and occurrence of lower T index subtypes.

Group E: subovoidal or anhedral crystals, with abraded edges, rounded corners and pitted faces. Typologic determination is not possible. These zircons may be largely recycled from sedimentary or metasedimentary source rocks.

Group F: subovoidal or anhedral grains which cannot be determined for several reasons (broken corners, faces hidden by dark material or by intergrowth with other minerals). This group also includes angular fragments and cracked grains, possibly broken during crushing of the samples.

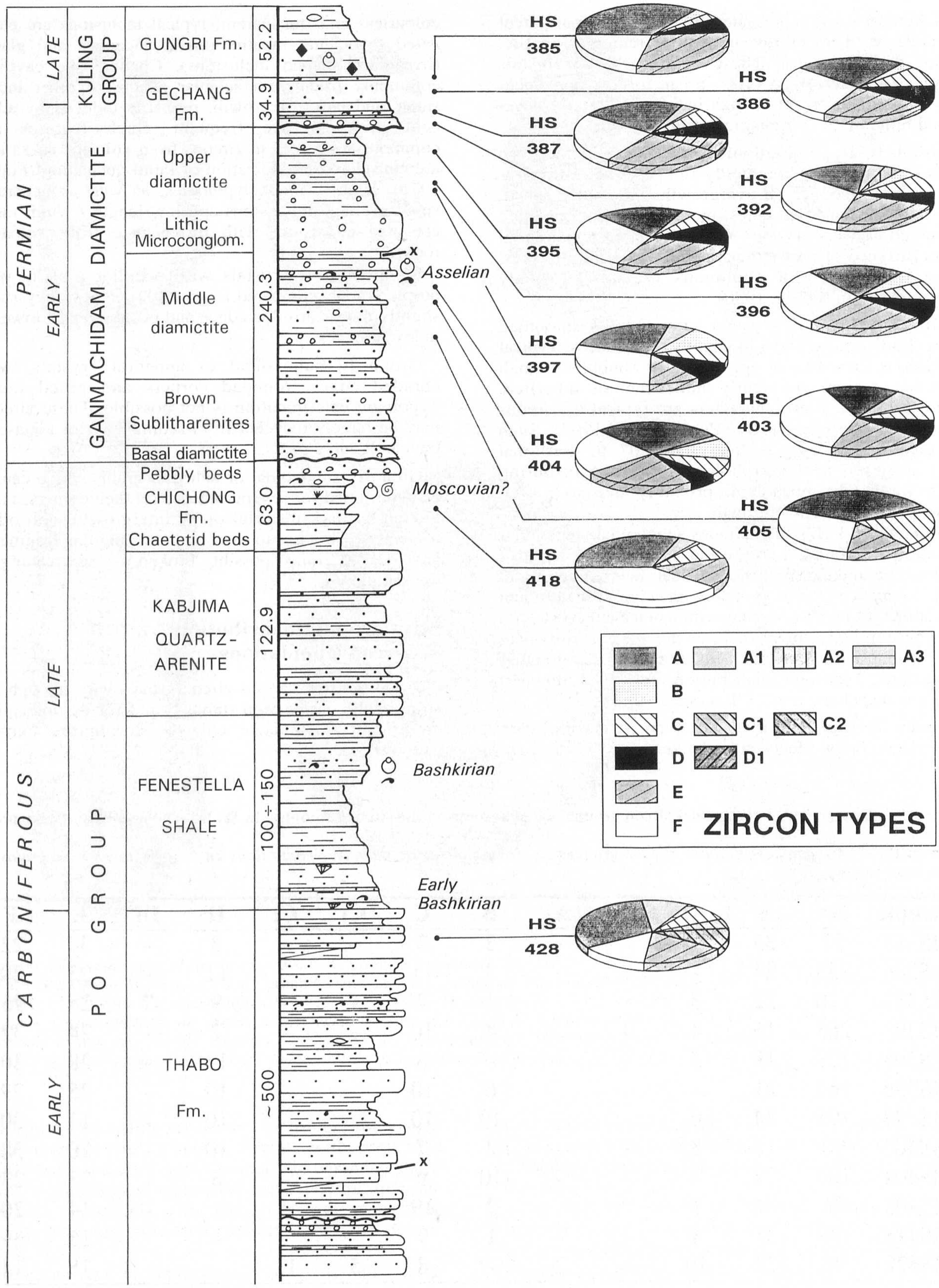
Stratigraphic distribution of zircon populations

Proportions of various zircon groups vary through the stratigraphic succession (table II and fig. 4), indicating significant provenance changes during the Permo-Carboniferous.

Table II. – **Occurrence of recognized zircon groups and subgroups in the studied samples, in %.** N° = number of analyzed zircon grains.

Tableau II. – ***Fréquence de groupes et sous-groupes de zircons identifiés dans les échantillons en %.*** *N°= nombre de grains de zircons étudiés.*

Sample	N°	A	A_1	A_2	A_3	B	C	C_1	C_2	D	D_1	E	F
HS385	37	35	-	-	-	3	3	-	-	8	-	30	22
HS386	133	24	-	-	-	3	11	-	-	11	-	23	29
HS387	110	22	3	-	-	1	7	-	-	9	7	25	25
HS392	263	16	4	4	-	4	10	-	-	7	-	24	32
HS395	129	19	3	-	-	-	6	-	-	13	-	28	30
HS396	161	21	-	-	-	6	10	-	-	10	-	25	29
HS397	105	24	6	-	-	10	10	-	-	10	-	11	30
HS403	90	16	8	-	-	2	7	-	-	10	-	20	38
HS404	100	27	2	-	-	10	9	-	-	6	-	23	23
HS405	94	34	1	-	-	2	19	-	-	-	-	14	30
HS418	138	31	4	-	-	1	9	-	-	-	-	15	39
HS428	96	32	10	-	2	-	8	5	11	-	-	18	14


PERMIAN
CARBONIFEROUS
LATE
EARLY
LATE
EARLY
KULING GROUP
GANMACHIDAM DIAMICTITE
PO GROUP
GUNGRI Fm.
GECHANG Fm.
Upper diamictite
Lithic Microconglom.
Middle diamictite
Brown Sublitharenites
Basal diamictite
Pebbly beds
CHICHONG Fm.
Chaetetid beds
KABJIMA QUARTZ-ARENITE
FENESTELLA SHALE
THABO Fm.
52.2
34.9
240.3
63.0
122.9
100 ÷ 150
~500
Asselian
Moscovian?
Bashkirian
Early Bashkirian
HS 385
HS 386
HS 387
HS 392
HS 395
HS 396
HS 397
HS 403
HS 404
HS 405
HS 418
HS 428
A
A1
A2
A3
B
C
C1
C2
D
D1
E
F
ZIRCON TYPES

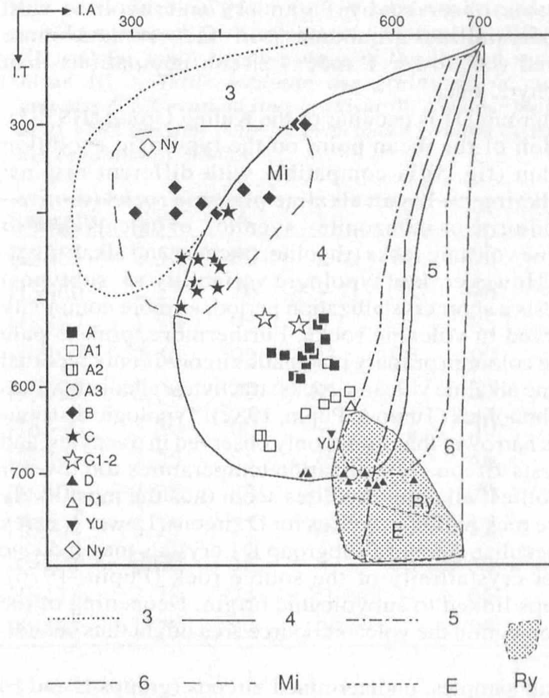


Fig.5. – **Mean points A/T of zircon groups and subgroups compared to typical fields of different rocks (after Pupin, 1976, 1985).** 3 : aluminous granites and granodiorites; 4 : calcalkaline (left) and K-calcalkaline (right) intrusive series; 5 : high-K intrusive series; 6 : alkaline granites; Mi : recrystallized zircons from anatectic migmatites; Ry : alkaline rhyolites; E : field of Estérel rhyolites and ignimbrites (Pupin, 1976). Also reported for comparison are the mean points of Nyimaling (Ny; Stutz, 1988) and Yunam (Yu; Spring *et al.*, 1993) samples.

Fig. 5 – ***Points moyens A/T des groupes et sous-groupes de zircons comparés aux champs typiques de différentes roches (d'après Pupin, 1976, 1985).*** *3 : granites et granodiorites alumineux; 4 : séries intrusives calco-alcalines (gauche) et calcoalcalines-potassiques (droite); 5 : séries intrusives potassiques; 6 : granites alcalins; Mi : zircons migmatitiques recristallisés; Ry : rhyolites alcalines; E : rhyolites et ignimbrites de l'Estérel (Pupin, 1976). Les points moyens des échantillons de Nyimaling (Ny; Stutz 1988) et Yunam (Yu, Spring* et al. *1993 sont reportés pour comparaison.*

Group A crystals occur in all samples, suggesting constant supply from the same source over a long period. Remarkable similarity in both typologic distributions and secondary characters leads to very similar mean points in all samples (maximum $\Delta A = 43$; maximum $\Delta T = 60$) (fig. 5); according to Pupin (1976), differences between samples from a homogeneous pluton do not exceed such values. This is consistent with the coherent typologic distribution obtained by adding the A populations from all the samples (fig. 6).

A1 crystals occur in most samples. They show narrow typologic distributions (3-7 subtypes); their mean points plot below those of A crystals (fig. 5). They may represent a population deriving from a source rock similar to, but distinct from that of A zircons. Alternatively, they may represent a subset of A group crystals that underwent different chemical or physical processes in sedimentary environments.

Subgroup A2 is identified only at the base of the Kuling Group (HS392). Typologic distribution is limited to 5 subtypes in the central-lower part of the typologic grid; the resulting mean point plots at some distance from both A and A1 populations, though along the same trend of the latter (fig. 5). Typologic characters suggest that zircon crystallization occurred in a calcalkaline magma in probably intrusive conditions.

Subgroup A3 occurs exclusively in the Thabo Fm. (HS428) and with very few crystals, but their similarity with zircons described in charnockitic rocks (Pupin, 1976; Duchesne *et al.*, 1987) makes their presence significant.

Group B crystals first appear (in very small amount) in the Chichong Fm. (HS418), reach their maximum in the Upper diamictite (HS397-396) and are lacking or rare (1-4 %) in the overlying samples. Typologic characters and mean points (fig. 5) are comparable in all samples, except HS397 and HS405, where typologies suggest a more evolved character of the magma. The comprehensive typologic diagram (fig. 6) shows the typical oblique distribution of aluminous granites of mainly crustal origin.

Group C zircons are present throughout the studied succession. Their relative abundance mainly ranges from 6 to 11%, with a higher frequency (19%) only in HS405. Mean points are similar and plot in an area which is consistent with recrystallized populations from migmatites (fig. 5). Typologic distribution of the total C population (fig. 6) is narrow along the A axis and wide along the T axis, as typical for anatectic migmatites.

Subgroups C1 and C2 are both peculiar of the Thabo Fm. (HS428). For subgroup C1, a comparison with literature data suggests provenance from granulites (Hoppe, 1962; Pupin, 1976), whereas the origin of C2 is more questionable. Occurrence of cores surrounded by transparent, inclusion-free overgrowths seems typical of zircons from high-grade metamorphic rocks, but their well developed {101} and {100} forms are rather unusual for these rocks. As recently pointed out by Pupin (1994), large cores with dominant {101} and {100} faces may influence the morphology of the overgrowth, leading to higher $\overline{A}$ and $\overline{T}$ indices than commonly observed in most migmatites.

Group D crystals first appear in the Middle diamictite (HS404) and are present through the overlying strata.

← Fig.4. – **Carboniferous to Permian stratigraphic column (Losar, Upper Spiti Valley).** Pie-charts show relative abundance of various zircon groups and subgroups through the section.

Fig. 4. – ***Colonne stratigraphique du Carbonifère au Permien (Lozar, vallée supérieure de la Spiti).*** *Les diagrammes camembert montrent l'abondance relative des différents groupes et sous-groupes de zircons le long de la coupe.*

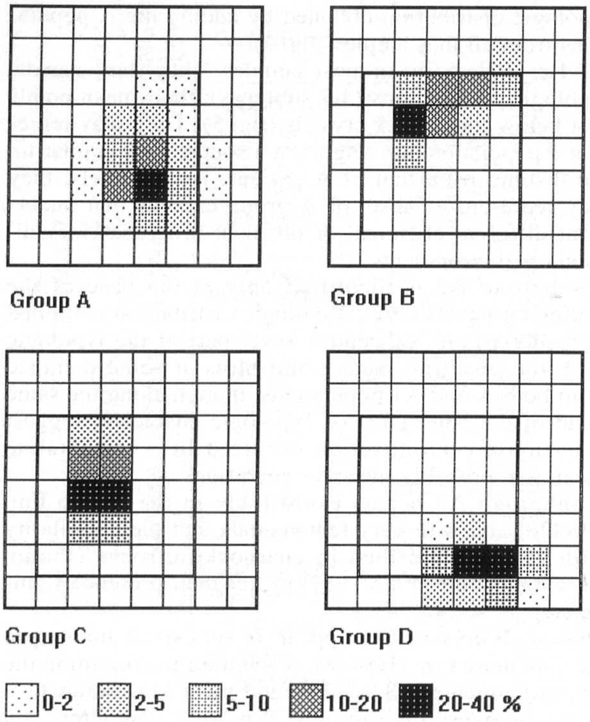


Fig.6. – **Typologic distributions of total A, B, C and D populations (sum of all crystals for each group in all samples).** Symbols indicate frequency of each subtype of the typologic grid shown in Fig.2.

Fig. 6. – ***Distribution typologique de toutes les populations A, B, C et D (somme de tous les cristaux pour chaque groupe, tous échantillons confondus).*** *Les grisés indiquent la fréquence de chaque sous-type de la grille typologique de la figure 2.*

Typologic distributions are limited to a few subtypes with prevailing {100} faces; high frequency of the supplementary bipyramid {301} is peculiar. The typologic diagram concerning the whole D group (fig. 6) shows regular distribution of frequencies around subtypes S24 and S25. Mean points of the samples plot in an area of the typologic evolution diagram where several fields overlap (fig. 5). Secondary features and occurrence of monoprismatic zircons (only exceptionally found in plutonic zircon populations) strongly suggest volcanic origin. Morphological characters, particularly the occurrence of P and D subtypes (fig. 6) and of the {301} supplementary bipyramid (= secondary subtypes U, N and T), are consistent with origin from alkaline (not peralkaline) rhyolites or ignimbrites. A good example of similar zircon populations is represented by the Permian rhyolites from the Estérel Massif (France; Pupin 1976, 1978; Tessier *et al.*, 1978), which define a similar trend with decreasing $\overline{A}$ index at constant or slightly decreasing $\overline{T}$ index (fig. 5). The slightly lower $\overline{T}$ indices of group D zircons as compared to Estérel populations hint at a higher degree of crystallinity of the rocks: as observed by Pupin (1976), rhyolites with microcrystalline groundmass in fact contain more evolved (i.e. lower $\overline{T}$ index) zircon populations than vitrophyric ones.

Subgroup D1 is peculiar of the Kuling Group (HS387). Position of the mean point on the typologic evolution diagram (fig. 5) is compatible with different origins: calcalkaline to K-calcalkaline plutonic rocks (diorite - granodiorite or monzonite - syenite), or calcalkaline to alkaline volcanic rocks (rhyolite, trachyte and alkali-rhyolite). However, low typologic variability (5 subtypes) suggests a short crystallization period, as more commonly observed in volcanic rocks. Furthermore, pink to pale purple colour in primary magmatic zircons is only reported in some alkaline volcanic rocks: trachytes, alkali-rhyolites and phonolites (Turco & Pupin, 1982). Typologic distribution is narrower than commonly observed in trachytes, and suggests zircon crystallization temperatures too low for phonolites; alkaline rhyolites seem thus the most likely source rock for D1 as well as for D zircons. Lower $\overline{T}$ index and peculiar colour of subgroup D1 crystals may indicate higher crystallinity of the source rock (Pupin, 1976), perhaps linked to subvolcanic origin. Deepening of the erosion within the volcanic source area might thus be indicated.

In all samples, undetermined zircons (groups E and F) represent about half of the observed grains (11 to 30% and 14 to 39% respectively; table II). Group E is particularly abundant at the top of the Ganmachidam Fm. (upper part of the "Upper diamictite") and in the Kuling Group, whereas lowest values are found in the Po Group (HS428, HS418).

Grain size versus zircon typology

In order to test the possible influence of grain size of sediments on zircon typologic distributions, we compared (table III) average grain size of zircons from the different groups, expressed as (L+l)/2, to median grain size of sandstone framework (GSZ; semiquantitatively evaluated according to the method described in Garzanti, 1986). Size of zircon grains and GSZ, however, do not appear to be necessarily related (e.g., finest-grained zircon populations for all groups except D are found in sample HS397 and not in the much finer-grained sample HS396) and only poor correlations (correlation coefficient 0.2 to 0.5; significance level >10%) are generally obtained (e.g., groups A and D; fig. 7). Correlation is lost for GSZ <2 ϕ (size of sieve mesh). Moreover, the homogeneous typologic characters of zircons from each group in different samples, in spite of marked grain-size variations, suggests that textural features have little influence on typologic distributions of detrital crystals, provided that a sufficiently wide grain-size fraction is analyzed (in the present work, <250 μm).

Other heavy minerals

Monazite with thorium content up to 6% in the Chichong Fm. (HS418) is consistent with provenance from intrusive rocks. A few ilmenite grains with Fe

Table III. – **Median grain size of sandstone framework (GSZ; expressed as Φ values) and average (L+l)/2 value (in μm) for main zircon groups in the studied samples.**
Tableau III. – ***Taille médiane des grains de la matrice gréseuse (GSZ exprimé sous la valeur Φ) et valeur moyenne de (L+l)/2 (en μm) pour les principaux groupes de zircons des échantillons étudiés.***

Sample	GSZ	A	A_1	B	C	D
HS385	2.50	90	-	80	92	29
HS386	2.25	76	-	108	48	63
HS387	1.50	95	117	-	85	78
HS392	2.50	92	93	90	90	99
HS395	0.00	77	84	-	67	88
HS396	3.50	60	-	72	50	51
HS397	2.25	55	76	62	46	77
HS403	2.25	83	69	-	70	95
HS404	0.25	71	48	60	52	79
HS405	0.00	56	-	66	54	-
HS418	2.75	74	81	-	66	-
HS428	1.75	89	109	-	93	-

tot/Ti ratio close to 1 and low magnesium content, recognized from the Chichong Fm. (HS418) to the Gechang Fm. (HS387), may have been derived from charnockites of the Indian Shield (Howie, 1955).

Cr-rich chromian spinel with average Cr# ratio = 0.80 ± 0.007, found from the Middle diamictite (HS403) to the lower Gechang Fm. (HS387), points to emplacement of mafic igneous rocks & rise of the astenosphere beneath the Indian Upper plate margin (Stampfli *et al.*, 1991; Gaetani and Garzanti, 1991) at the climax of rifting in the earliest Permian.

DISCUSSION

The Thabo Fm. (HS428) is characterized by zircons from calcalkaline granitoids or orthogneisses (group A), and high-grade metamorphic rocks (migmatites: C and C2; granulites: C1; possibly charnockites: A3), and thus seemingly derived from the Indian Shield in the South. Occurrence of A and C zircons throughout the Carboniferous and Permian succession suggests that detritus from the Indian Shield remained a main component of the terrigenous sediments during the whole rifting stage, until the final development of the Indian passive margin. These conclusions are based on the unproved, though reasonable, assumption that all typologically identified zircons of groups A and C are "first cycle" grains. However, we cannot exclude that even a significant part of them are in fact polycyclic and derived from Precambrian or lower Paleozoic sedimentary rocks, in turn ultimately fed by the Indian continental block.

Group B zircons, first appearing at the top of the Po Group (HS418) and becoming abundant in the "Upper diamictite", document erosion of a new type of granitoid rocks of mainly crustal anatectic origin. Modal analysis also reveals that granitoid detritus is renewed in the Chichong Fm. and peaks in the "Upper diamictite" (Garzanti *et al.*, 1995a). Since the varying relative abundance of sedimentary fragments within the Ganmachidam Diamictite is consistent with unroofing of Upper to lower Paleozoic successions at this stage of active inversion of sedimentary basins, it is likely that rapid uplift of rift shoulders around the end of the Carboniferous led to erosion of anatectic granitoids of

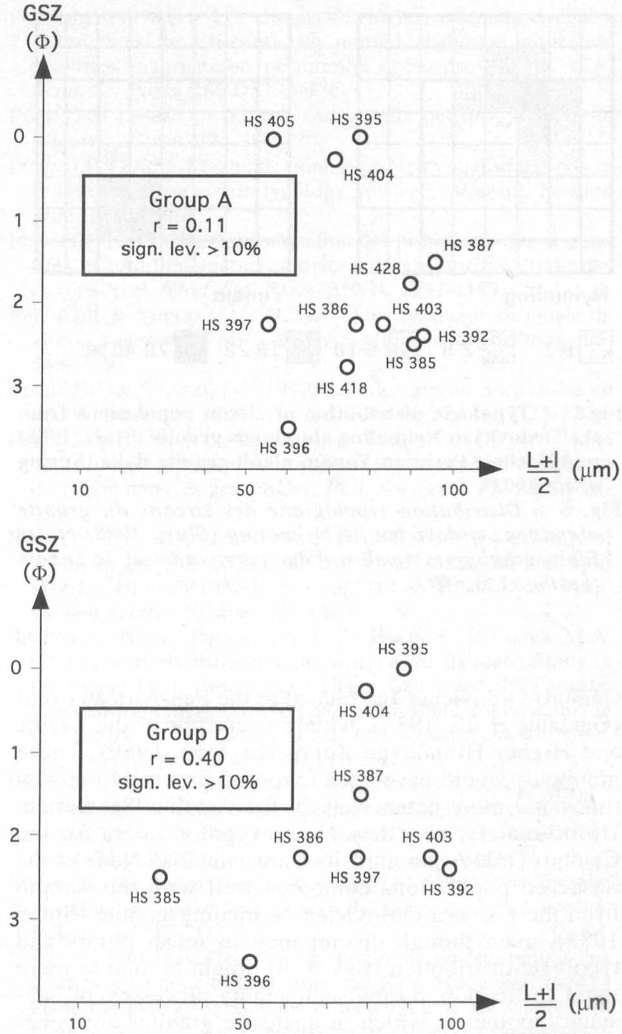


Fig.7. – **Comparison between average dimensions (L+l)/2 (in μm) of zircons from group A and group D and median grain size GSZ (in Φ values) of sandstone framework.**
Fig. 7. – ***Comparaison entre les dimensions moyennes (L+l)/2 en μm des zircons du groupe A et du groupe D et les tailles médianes des grains (GSZ en valeur Φ) de la matrice gréseuse.***

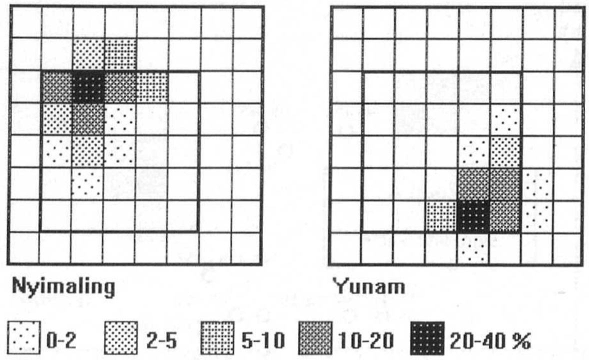


Fig.8. – **Typologic distribution of zircon populations from the Ordovician Nyimaling aluminous granite (Stutz, 1988) and Earliest Permian Yunam alkali-granite dyke (Spring *et al.*, 1993).**

Fig. 8 – ***Distribution typologique des zircons du granite alumineux ordovicien de Nyimaling (Stutz, 1988) et des filons granitiques alcalins d'âge permien basal de Yunam (Spring* et al. *1993).***

Cambro-Ordovician age related to the Pan-African event (Garzanti *et al.*, 1986), widely occurring in the Lesser and Higher Himalayan Zones (Le Fort, 1989). These granitoids would have been unroofed first in Moscovian times and more extensively in the Asselian/Sakmarian. Unfortunately, very few zircon typology data for the Cambro-Ordovician intrusions are available. None of the observed populations compares well with the sample from the Cambro-Ordovician Nyimaling granite (Stutz, 1988), even though discrepancy in mean points and typologic distribution (figs. 5, 8), might be due to more rapid destruction, during sedimentary processes, of late-stage typologies, which in anatectic granites are generally partly metamict.

The Ganmachidam Diamictite contains zircons from alkaline rhyolites (group D) associated with chromian spinel. Bimodal volcanic detritus, including lathwork to felsitic rock fragments, is typical of rift magmatism. Occurrence of pink-purple zircons (D1) in the Gechang Fm. (HS387) suggests provenance from igneous rocks with higher porphyritic index, hinting at a subvolcanic origin. Mean point for the D1 population plots not far from that of Yunam granite dyke (fig. 5; Spring *et al.*, 1993). Even though the Yunam granite shows a much wider zircon typologic distribution (fig. 8), possibly due to a longer crystallization period in deeper conditions, it is very likely that group D zircons were derived from alkaline rhyolites belonging to the same magmatic suite as the Yunam granite. The Asselian age, paleontologically established for the Ganmachidam Diamictite (Garzanti *et al.*, 1995a), is consistent with the radiometric age of 284 ± 1 for the Yunam granite (Spring *et al.*, 1993) and suggests erosion of this magmatic suite soon after emplacement.

Finally, increasing abundance of group E (recycled?) zircons from the Po Group to the Kuling Group is consistent with major recycling of siliciclastic successions and upward increase of sandstone rock fragments in the Ganmachidam Diamictite.

Conclusions

The zircon typology method, applied to the classical Permo-Carboniferous succession of the Spiti Tethys Himalaya, proved to be a useful tool to discriminate between felsic igneous rocks emplaced or unroofed during rifting.

A large part of detrital zircons (groups A and C) were most likely derived from the Indian Shield to the south during the whole of the Carboniferous and Permian.

Appearance of group B zircons in Upper Carboniferous sediments hints at rejuvenation of a Pan-African belt, including widespread anatectic granitoid bodies of Cambro-Ordovician age.

Volcanic zircons (group D), along with Cr-rich chromian spinel, first occur in Asselian glaciomarine sediments, reflecting the onset of felsic to mafic bimodal alkaline magmatism during the climax of rifting.

Increase of "recycled" zircons (group E) in the Permian is consistent with extensive recycling of progressively older siliciclastic successions due to unroofing of the rapidly uplifted shoulders of the rift.

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