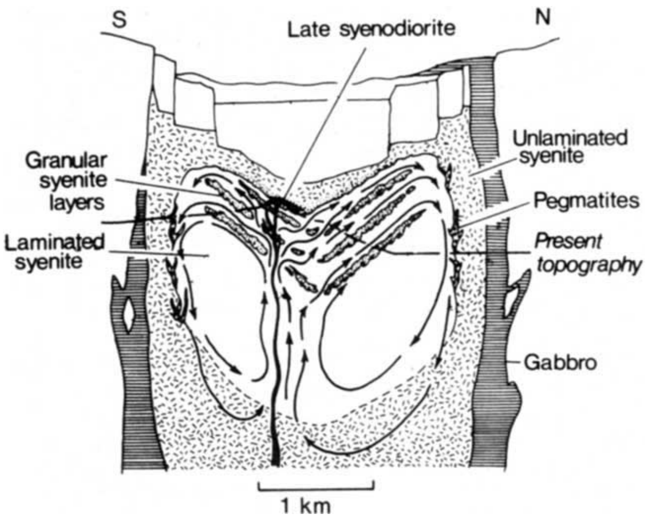

Fig. 4 Stylized section through the Klokken chamber showing suggested flow-lines (arrows) for the deuteric fluid and the disposition of the main rock units. Although the thickness of the layered series (laminated + granular syenites) is approximately correct[4] (equal horizontal and vertical scales), for clarity the thickness of the granular layers is greatly exaggerated (real thickness 0.1-30 m) and their number underestimated (there are ~40 granular layers in the exposed section, and they become thicker and more abundant upwards)[5,12]. The caldera superstructure is speculative.

syenite feldspars have leaked argon in proportion to their turbidity[14]. We conclude that the coarse-grained, drusy laminated syenite layers acted as high-temperature aquifers in the layered complex, over at least the temperature range 850-450 °C, probably corresponding to a cooling interval of $>10^5$ yr (ref. 13). The relatively fine-grained, compact-textured granular layers acted as impermeable horizons. Variable permeabilities account for the irregular relationships observed across layers at single localities (Fig. 3). Generally, the mafic parts of inversely graded layers have feldspars which are less turbid than those in leucocratic parts, suggesting that the mafic layers were less permeable than the leucocratic syenite.

Fluid circulation has been modelled numerically for the Skaergaard intrusion[15], which water is thought to have entered from the well-jointed basalt envelope. In contrast, the Klokken layered series was sealed against the ingress of water by the outer gabbro and unlaminated syenite rings (Fig. 4). Biotites in the gabbros form a series with OH/F ratios different from those in all syenites, suggesting that they were in equilibrium with a different fluid (I.P., R. A. Mason and S.M.B., in preparation).

Although the late syenodiorite intrusion strongly influenced the mineral chemistry in its vicinity, it seems unlikely that this comparatively small body would have provided the heat source necessary to drive kilometre-scale convection in the entire chamber. The summit sheet is thin, and the feeder dyke is only ~3 m wide at its intersection with layer R (Fig. 1). We envisage an initially symmetrical convecting system upon which the thermal effect of the late-arriving syenodiorite was superimposed (Fig. 4), causing a local perturbation in the flow regime.

The roof of the complex was close to the present level of erosion[7], and Fig. 4 shows an axial rise of heated water from the comparatively slowly cooling interior; this water is then constrained to move laterally along inclined laminated syenite aquifers beneath the roof. Pyroxenes in equilibrium with this fluid were more Na- and Fe-rich in the cooler, outer part of the system, and in the inner core the mineralogy of the layered series was modified by the emplacement of the more basic syenodiorite. Klokken is unusual in that its laminated syenites crystallized from a residual magma which was at or near water-saturation[5]. Large-scale modification of mineralogy may be unlikely in more basic intrusions. We note that the discordant mineral variation found in the Skaergaard intrusion[10] occurs at the junction between the Upper Zone and the Upper Border Group, a situation analogous to the granular syenite/laminated syenite boundary at Klokken. Although infiltration metasomatism has been postulated as a post-cumulus source of mineral modification in the Muskox intrusion[16], this is a local re-equilibration with intercumulus silicate liquid. It is improbable that the effects at Klokken could result from kilometre-scale circulation of intercumulus melt, particularly in view of the relatively low temperature and high silica content of the residual liquid. Circulation of residual melt is also unlikely because individual layers tend to have distinctive intercumulus assemblages (for example, quartz is found only in certain layers, as is intercumulus sphene).

In the Klokken intrusion, sub-solidus modification of the consolidated sequence by deuteric fluids appears to have produced compositional variation very similar to that usually ascribed, in layered complexes, to crystal-melt fractionation. Although most salic plutons are not layered, they almost invariably exhibit low-temperature deuteric alteration, and by analogy with Klokken, substantial changes in mineral chemistry may also accompany the circulation of fluids at high temperatures during their cooling history.

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Jack Hills, evidence of more very old detrital zircons in Western Australia

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The age of the Earth's oldest crustal minerals sets a time-limit on the earliest preservation of buoyant solid crust. The oldest mineral ages reported so far are ~4,180 Myr for detrital zircons from quartzites at Mount Narryer[1], in the Yilgarn Block, Western Australia. The oldest-known intact rocks, as distinct from individual minerals, are substantially younger; they formed ~3,813-Myr ago[2] in the Isua supracrustal belt, West Greenland. We report here a further occurrence of old detrital zircons, again identified using the ion-microprobe SHRIMP[3], in conglomerate from the Jack Hills Metasedimentary Belt[4,5] (26°11′ S, 116°58′ E),

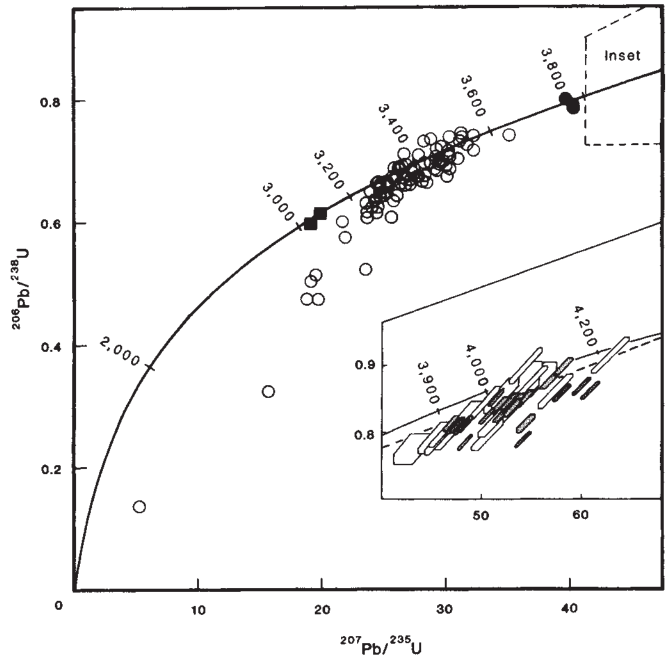

Fig. 1 Conchordia diagram showing U-Pb ages by ion microprobe for 140 grains of detrital zircon from Jack Hills conglomerate sample W74. All points on the main diagram and the open symbols in the inset are reconnaissance analyses. The filled symbols in the main diagram denote concordant ages for the youngest and oldest grains in the younger population, and those in the inset are precise analyses. The inset shows the complete data (Table 1) for the 17 oldest grains. Uncertainties are one standard error. The broken line is a hypothetical early Pb-loss line to 3,500 Myr.

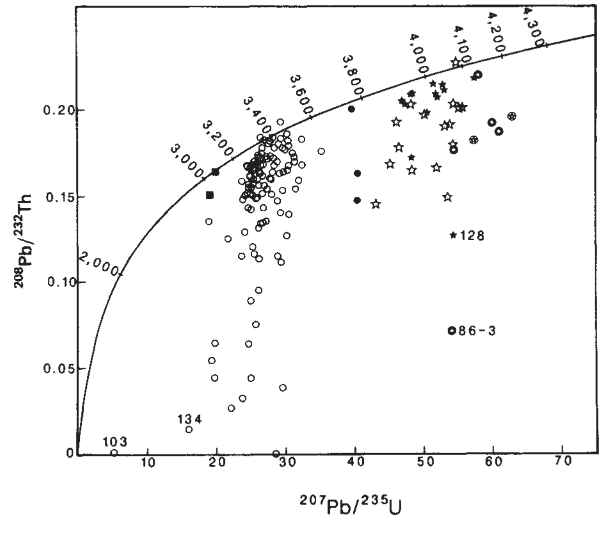

Fig. 2 Concordia-type diagram showing Th-Pb ages. Symbols are as for Fig. 1, except that analyses of the older crystals are shown as stars. ☆, reconnaissance; ★, precise analyses; circled stars, grain 86.

~60 km north-east of Narryer. This discovery is important for several reasons. First, one zircon registers the exceptionally old age of 4,276±6 Myr, which is, moreover, a minimum estimate for its original age; 16 other grains may have the same age or may be slightly younger. Second, the new occurrence considerably extends the area over which the old Narryer suite is known, thus amplifying its geological significance. Third, the frequency of old zircons in the Jack Hills occurrence is 12%, about five times higher than at Narryer, which suggests that the intact ~4,180 Myr-old rocks, if they still exist, might be closer, and facilitates future comparison of the SHRIMP data with conventional analyses of these grains. (Recent conventional U-Pb work[6] on other zircons from the same Narryer concentrate confirmed the younger ages but failed to observe any at ~4,180 Myr, probably because of their low abundance[7]). The likelihood that zircon would dissolve in magmas undersaturated in zirconium[8] argues against its survival in long-term contact with such magmas during the disaggregation and subduction of crust. Consequently, the existence of zircon in the Jack Hills area from ~4,300 Myr ago implies that this part of the crust has been preserved, since then, from recirculation in the mantle through plate-tectonics or any other mechanism.

The Jack Hills Metasedimentary Belt is a narrow belt ~70 km long composed of minor metabasalts and thick chert and banded iron formation interleaved with clastic metasediments[5]. It is broadly similar to the nearby Narryer Metamorphic Belt[9] but lower in metamorphic grade (high greenschist). It is separated from surrounding granites and gneisses by zones of major deformation which prevent direct observation of the relative ages of the granitic rocks and the belt. Some of the granites have been dated using conventional zircon U-Pb techniques as ~3,500 Myr (gneissic granite) and ~2,600 Myr (undeformed granite)[5]. The detrital zircons were concentrated from a chert pebble conglomerate within a thick clastic sequence in the southwestern section of the belt. They vary from almost colourless to deep purplish brown, and are predominantly broken (probably during processing) and rounded. Most of the latter are pitted suggesting transport abrasion. Rare grains have a blunted prismatic form. Only a few are structured into a core surrounded by a distinct rim of younger zircon. Several analysed grains show faintly the euhedral internal zoning that is generally considered to result from magmatic crystallization, but none of the 4,100–4,300-Myr-old zircons (hereafter termed the 'old' zircons) have this feature. Most of the zircons are devoid of inclusions although some, including three old grains, contain a few randomly oriented, transparent, acicular inclusions. The 17 old zircons identified cannot be distinguished on colour or morphological criteria from the other rounded grains.

The U-Pb results are plotted in Fig. 1, which shows that the analyses of most zircons lie either within error of Concordia or slightly below it, signifying only small losses in their uranogenic Pb. In contrast, a few areas within grains have lost much of their radiogenic Pb comparatively recently. For concordant zircons and those having Pb loss at zero-age only, the original ages are calculable from the radiogenic $^{207}Pb/^{206}Pb$. Where the Pb-loss history is more complex, the $^{207}Pb/^{206}Pb$ ages can be interpreted reliably as minimum estimates for the original ages. (We emphasize that Pb isotopic ratios are directly measured without peak-stripping on SHRIMP and are independent of standard comparisons and calibrations; as such they provide straightforward minimum age-determinations for each analysed area.) The $^{207}Pb/^{206}Pb$ age for most grains is ~3,350 Myr, which we interpret as their age of crystallization or high-grade metamorphic recrystallization before deposition in the conglomerate. Those between 3,400 and 3,600 Myr (Fig. 1) probably represent older zircons that formed at different times within that interval, and there are several grains that formed earlier still at ~3,800 Myr. Two zircons are distinctly younger than all the rest with concordant ages at just less than 3,100 Myr. They are detrital, having rounded forms and abraded surfaces, and their age constrains the deposition of the conglomerate to later than that value. The $^{207}Pb/^{206}Pb$ ages that exceed 3,900 Myr belong to a much older population which may have had a single original age close to 4,300 Myr and have undergone early as well as recent Pb loss, or it may be a mixed-age population that formed during discrete events over an extended time period from 4,100 to 4,300 Myr ago.

The details of reconnaissance and precise analyses of the 17 old zircons are listed in Table 1. The five analysed areas within grain 86, which shows the highest minimum ages, exhibit small

Table 1 Ion microprobe analyses for U, Th and radiogenic Pb for 25×35 μm areas within the older zircons from Jack Hills

Grain-area	U (p.p.m.)	Th (p.p.m.)	% Common 206*	208/232	206/238	207/235	207/206	Minimum age (Myr)
22-1R	49	25	3.4	0.180±23	0.880	54.4	0.448±8	
22-1P	56	24	0.6	0.172±6	0.784	48.3	0.446±2	4,072±7
31-1R	55	22	4.2	0.166±26	0.854	51.9	0.441±7	4,055±24
34-1R	217	113	1.0	0.197±8	0.843	50.2	0.432±3	
34-2P	82	34	0.6	0.195±6	0.824	50.4	0.444±2	4,065±7
43-1R	39	27	9.7	0.149±27	0.857	53.6	0.453±12	
43-1P	46	33	1.4	0.206±7	0.826	51.9	0.456±3	4,105±10
46-1R	57	23	4.4	0.165±27	0.821	48.4	0.427±8	4,007±28
51-1R	70	47	3.4	0.178±14	0.797	46.5	0.423±7	
51-1P	71	47	0.2	0.209±5	0.808	47.9	0.430±2	4,017±7
53-1R	32	20	7.2	0.145±33	0.774	43.1	0.403±13	3,920±48
56-1R	149	95	0.6	0.227±9	0.873	54.9	0.456±3	
56-1P	160	104	0.3	0.214±9	0.846	52.7	0.452±2	4,092±7
82-1R	39	25	3.2	0.201±19	0.878	55.6	0.459±8	
82-1P	47	30	0.7	0.211±6	0.836	53.0	0.460±3	4,118±10
86-1R	96	58	2.5	0.182±10	0.861	57.4	0.483±4	
86-1P	115	70	0.5	0.220±5	0.859	58.0	0.490±2	4,211±6
86-2R	174	152	1.0	0.196±6	0.915	62.9	0.499±3	
86-2P	187	156	0.5	0.192±5	0.868	60.0	0.501±2	4,244±6
86-3P	181	327	0.9	0.071±2	0.789	54.1	0.497±2	4,232±6
86-4P	113	87	0.5	0.187±4	0.862	60.9	0.512±2	4,276±6
86-5P	40	20	2.1	0.175±8	0.811	54.4	0.485±4	4,196±12
92-1R	59	26	3.3	0.169±19	0.791	45.1	0.414±6	3,961±22
102-1R	174	77	1.4	0.203±9	0.899	54.4	0.439±3	
102-1P	165	76	0.1	0.215±3	0.852	51.4	0.438±2	4,045±7
119-1R	186	108	0.7	0.193±6	0.801	46.1	0.418±3	
119-1P	198	112	0.2	0.205±3	0.812	46.9	0.418±2	3,975±7
119-2P	182	102	0.5	0.209±4	0.840	51.8	0.447±3	4,075±10
P	177	95	0.1	0.209±4	0.812	48.3	0.431±3	4,021±10
123-1R	61	24	1.9	0.190±18	0.828	52.4	0.459±6	4,115±19
123-1P	70	28	0.8	0.225±10	0.898	58.2	0.470±3	4,150±9
	71	28	0.5	0.212±8	0.877	56.8	0.470±3	4,150±9
128-1R	77	23	2.3	0.182±21	0.816	51.2	0.455±5	4,102±16
128-2P	93	53	1.0	0.123±5	0.850	54.3	0.463±3	4,128±10
	101	54	0.4	0.130±5	0.845	53.4	0.458±3	4,111±10
130-1R	114	41	1.0	0.193±12	0.789	45.7	0.420±4	3,982±14
130-1P	123	44	0.6	0.201±7	0.810	47.2	0.423±3	3,993±11
	127	45	0.3	0.205±5	0.811	47.5	0.425±2	4,000±7
138-1R	91	57	2.3	0.180±11	0.796	50.5	0.461±5	4,121±16

Analytical procedures are described elsewhere[2]. Uncertainties shown are one standard error and refer to the last digits only. Coefficients of variation are 1.5% for precise Pb/U, 3.0% for Th/U and reconnaissance Pb/U, and 10% for U, Th concentrations.

R, Fast reconnaissance analysis using three scans.

P, Precise analysis using 14 scans and lower content of surface-related common Pb.

* Surface-related common Pb, taken as Broken Hill ore; sample 206/204 is 1600/(% common 206).

but real differences in radiogenic $^{207}Pb/^{206}Pb$ that can only have been generated by internal redistribution or loss of radiogenic Pb relative to U at some early time. The slightly discordant distribution of U–Pb data within this grain and all except possibly one of the other old grains (Fig. 1) is similar to that observed in many zircon suites in Archaean rocks elsewhere, and is customarily explained by minor Pb loss during one or more later events. Nevertheless, another conceivable explanation involves an early gain of Pb (or loss of U) followed by recent Pb loss, which would have the effect of increasing the $^{207}Pb/^{206}Pb$ age of the zircons. Redistribution of Pb that resulted in such 'reverse' discordance (points above Concordia) has been reported[10] for three out of seven areas analysed in one exceptional zircon from an orthogneiss at Mount Sones (Napier Complex, Antarctica), but the phenomenon of reverse discordance is very rare. In view of this and the overall consistency of the slightly (normally) discordant data for the old zircons, such a complex and *ad hoc* mechanism involving reverse discordance followed by recent Pb loss is considered most unlikely as an explanation of the observed old U–Pb ages. Grain 86 also shows large differences in Pb/U between areas having the same $^{207}Pb/^{206}Pb$, which indicate recent Pb loss. Because there have been two or more apparently independent Pb loss events, a single Pb loss vector in Fig. 1 cannot be constructed for grain 86 to estimate its original age of crystallization. All that can be said is that 4,276±6 Myr, the highest $^{207}Pb/^{206}Pb$ age listed in Table 1, is most likely a minimum estimate for the original age.

Additional evidence for recent Pb loss from many of the zircons, including grain 86, is shown in Fig. 2, a Concordia plot of $^{208}Pb/^{232}Th$ against $^{207}Pb/^{235}U$. Many of the analysed zircons are close to Concordia on this diagram, but assuming no U or Th movement, many others have lost ^{208}Pb relative to ^{207}Pb. The reliability of Th/U and Pb/U as measured by SHRIMP has been documented elsewhere[3], so that the differential loss of Pb isotopes (which has also been seen elswhere[11]) is a property of particular areas of zircon. The timing of this loss is equal to or younger than the youngest observed $^{208}Pb/^{232}Th$ age, which within error is zero. None of the data fall above Concordia, indicating that only Pb losses are registered rather than both gains and losses. The area showing the greatest loss of ^{208}Pb, 86-3, also has the lowest $^{207}Pb/^{235}U$, and the other zircons that are most discordant in Pb/U such as grains 134 and 103, also have the lowest $^{208}Pb/^{232}Th$. A plausible hypothesis is that all the old zircons first formed at ~4,300 Myr, then lost Pb during one or more early events such as the known felsic magmatism at ~3,500 Myr and the uplift and weathering of the zircon provenance at ~3,100 Myr. Their present compositions would lie on the hypothetical chord shown in Fig. 1 if no Pb had been lost subsequently. Instead, because Pb loss also occurred recently, they are variably scattered below it.

In the absence of other evidence, we have attempted to use the internal structure, morphology and Th, U contents of the detrital zircons to suggest the nature of their original source rocks. The nearly universal rounding of the zircons is ambiguous, as we cannot ascertain how much of the rounding is due to mechanical abrasion and how much to metamorphic corrosion. The most important genetic features of the 140 analysed zircons are the lack of internal structure and the lack of inclusions in most grains, the blunted euhedral forms of some zircons, and the faint euhedral zoning in the rest. Their mean U, Th, at about 100 and 50 p.p.m. respectively, is distinctly low relative to the average crustal zircon, and zircons with similar morphological features and with low U and Th contents are known in only a few rock types. Zircon populations made up almost entirely of coarse, rounded, uranium-poor, transparent, inclusion-free, unzoned zircon occur in pyroxene granulites[12]. Consequently, we favour mafic rocks that experienced granulite facies metamorphism as the probable sources for most of the detrital zircons from the Jack Hills conglomerate. In contrast to the old zircons from Jack Hills, all but one of those from Narryer have distinctive subhedral forms and pronounced euhedral internal zoning. The Narryer zircons also have significantly higher uranium, but not thorium, contents. These differences suggest that the zircons in the Narryer quartzite came from felsic igneous rocks not recrystallized by granulite grade metamorphism, and provide evidence for considerable geological complexity in the ancient terrain contributing zircons to the two metasedimentary belts.

The ion microprobe analyses were largely made by I. S. Williams and P. D. Kinny who also reviewed the text, and J. J. Foster prepared the diagrams. Geological mapping and sampling in the Jack Hills were done in association with S. A. Wilde and J. L. Baxter assisted by WAIT students. Field work and R.T.P.'s participation in this project were supported by the Australian Research Grants Scheme.

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Carbon-14 dates point to man in the Americas 32,000 years ago

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The view that man did not arrive on the American continent before the last glaciation has been supported by the fact that until now the known and dated archaeological sites have not been of very great antiquity. But now we report radiocarbon dates from a Brazilian site which establish that early man was living in South America at least 32,000 years ago. These new findings come from the large painted rockshelter of Boqueirao do Sitio da Pedra Furada, the walls and the ceiling of which are decorated with a rich set of prehistoric paintings. We have excavated a sequence containing abundant lithic industry and well-structured hearths at all levels. Carbon-14 dates from charcoal establish a continuous chronology indicating human occupation from 6,160±130 to 32,160±100 years BP. A date of 17,000±400 BP, obtained from charcoal found in a level with fragments of a pictograph fallen from the walls, testifies to the antiquity of rupestral art in this region of Brazil.

The site of Boqueirao of Pedra Furada is one of the 200 known painted rock-shelters located in a remote region of the Brazilian plateau famous for its richness in prehistoric rupestral art (Fig. 1). This site, discovered in 1973 by the French-Brazilian archaeological mission in Piaui, is a rock-shelter situated on the steep bank of a 100-m non-calcareous sand-stone cliff, standing 20 m above the bottom of the valley of Pedra Furada.

The first excavation campaign at the site of Boqueirao of Pedra Furada was undertaken to date the rupestral art which is abundant in the region, and the first two dates obtained were from 7,640 ± 140 yr (Gif-4928) and 8,050 ± 170 yr BP (Gif-4625)[1]. The excavations were extended in area and depth during the following years. In 1985, the bedrock was finally reached after more than 3 m of sediment had been excavated.

Traces of human occupations succeed one another throughout the stratigraphic sequence. Based upon the distribution and number of artefacts which were in any case associated with the hearths, it appears that the site was occupied only by a small human group on temporary basis. The first traces of human presence in the shelter are a few scattered pieces of charcoal and two lithic pieces, found in the lowest layer A. These were a large pebble bearing the scars of several flakings, and a flake. This lowest level could not be dated.

All of the sedimentary layers contained remains which can be classified, according to the lithic industry and the type of structures of the hearths, in two main stages called Pedra Furada and Serra Talhada[2]. The artefacts unearthed in the surface layer E are different from those found in the lower layers, but not characteristic enough to permit definition of a cultural phase.

During the most ancient cultural phase, Pedra Furada, large circular hearths are found. They are well built with fallen blocks and contain large quantities of charcoal and ash. Lithic industry is abundant and localized around the hearths. The raw materials used for the fabrication of tools were quartz and quartzite, from the pebbles present at the site. Based upon typological and archaeological criteria, this cultural phase has been divided into four stages. In the earlier stage, Pedra Furada I, a lithic collection composed of 560 pieces was found, principally pieces with blunt points obtained by two, three or four convergent flakings, made of pebbles or flakes. Besides these typical tools, pebble-tools (chopping tools and choppers) appear as well as denticulates, burins, notched pieces, retouched flakes and double-edged flakes (Fig. 2).

In addition to the retouched pieces, the collection includes pebble-hammers, flaked pebbles, flakes and fragments produced by flaking. In this level, fragments of painted rock, fallen from the walls, are perhaps evidence of the ancient practice of rupestral art. Two dates, 31,700 ± 830 yr (Gif-6652) and 32,160 ± 1,000 yr (Gif-6653) have been obtained from charcoal coming from the first hearth found at the site.