EFA-LOG - The upper 3 km of the KTB-Hauptbohrung

R. PECHNIG & J. WOHLENBERG
RWTH Aachen, Lehrgebiet für Angewandte Geophysik, Lochnerstr. 4-20, 52064 Aachen

Summary

The main target of the research project EFA-LOG is the reconstruction of the lithology of the drilled through rocks in the scope of the Continental Deep Drilling Project (KTB), by using borehole-geophysical measurements. HAVERKAMP & WOHLENBERG (1991) developed a log interpretation technique enabling a transformation of logging responses to lithological characteristics also for crystalline rocks. Based on this method, succesfully tested in the KTB-VB, also for the uncored section from 280 m to 3000 m of the KTB-HB an unbroken synthetic lithological profile, the EFA-LOG, could be reconstructed. In contrast to the extensively measured KTB-VB only the logs of NGS, DLL and SDT were available for the interpretation of the first 3 km of the KTB-HB. Nevertheless 16 of 37 electrofacies calibrated at the lithology of the KTB-VB could be transferred to the logs of the KTB-HB in so far, that besides various gneiss- and amphibolitevarieties, also metagabbros and cataclastic or faulted zones could be reliably differentiated in the resulting EFA-LOG. Even for hitherto unobserved lithotypes, like the plagioclas-rich gneisses, a clear identification was possible. To established an EFA-LOG from only a few geophysical data sets will be important to reconstruct deeper sections of the KTB-HB when high temperatures will limit data acquisition.

Introduction

To understand the lithological conditions of the crystalline basement drilled through is one of the major objectives of the KTB-project. To reach this target the application of borehole-measurements is of fundamental importance, especially when cores are taken only rarely and geophysical logs are, besides the cuttings, the most important information available, as is the case for the *KTB-Hauptbohrung* (KTB-HB). Geophysical logs, as a continuous in situ vertical data set reflect crystalline lithologies very well. This was shown by HAVERKAMP & WOHLENBERG (1991) when they applied a newly developed method to reconstruct the lithology of the KTB-Vorbohrung (KTB-VB). To calibrate geophysical data with the well-known lithology of the almost completely cored pilot hole an extensive database was built up characterizing all differentiated lithotyps by specific electrofacies patterns. The result was a synthetic lithological profile called EFA-LOG. Now the objective is to use the EFA-LOG to reconstruct the lithology of the KTB-HB assuming a similar lithology at both drill sites. In the following the results of the upper 3 km of the KTB-HB will be presented.

Method and Quality Control

The method is based on a calibration of the borehole measurements with the drilled lithology correlating the logs with all available petrographical, geochemical and petrophysical data for the rocks. So each differentiated lithological unit, normally characterized by a specific mineralogical composition, will be classified by an individual set of log responses. This resulting electrofacies stores the definite minimum and maximum values of all logs used for each lithotype distinguishing one lithotype from all the others. The application of the calibrated electrofacies to the logs results in a continuous lithological profile, the EFA-LOG (HAVERKAMP & WOHLENBERG 1991).

With this approach 37 different electrofacies were defined in the KTB-VB, each one classified by 18 geophysical logs. Due to the reduced measuring program only six of these parameters (SGR, POTA, THOR, URAN, LLD and DT) are available for the EFA-LOG to reconstruct the section 280 - 3000 m of the KTB-HB (for the first 280 m no data are available). According to experiences gained in the pilot hole LLD and DT mainly reflect structural properties like cataclastics, faults and fissure zones. Being strongly affected by the anisotropy of the drilled rocks electric and sonic data are less suitable for detailed lithology determination. In contrast NGS data reflect lithological variations very well thus most of the calibrated electrofacies are discriminated by these logs.

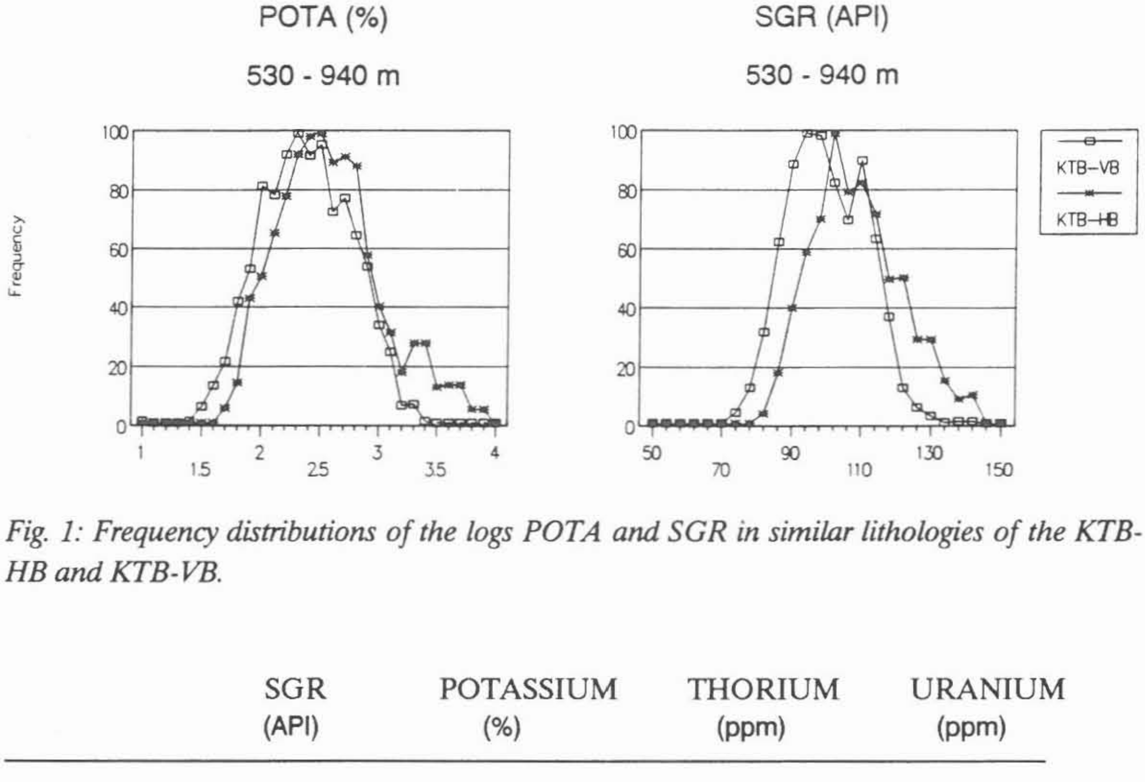

POTA (%)
530 - 940 m
SGR (API)
530 - 940 m

Fig. 1: Frequency distributions of the logs POTA and SGR in similar lithologies of the KTB-HB and KTB-VB.

	SGR (API)	POTASSIUM (%)	THORIUM (ppm)	URANIUM (ppm)
GNEISSES	+ 7	+ 0,15	+ 0,5	+ 0,8
METABASITES	+ 5	+ 0,20	+ 0,1	+ 0,4

Table 1: Average destinations of the KTB-HB NGS data in relation to the KTB-VB.

Transferring the electrofacies to the KTB-HB requires an extensive quality control including a comparison of the NGS logging data with laboratory measurements on cuttings as well as with KTB-VB logging data. Generally the correlation between laboratory and borehole measurements for the gamma ray and the evaluated contents of potassium, thorium and uranium is obvious. In order to check the logs also for slight differences between KTB-HB and KTB-VB a comparision of the data obtained from similar lithological sections was carried through. The NGS data of the KTB-HB are systematically shifted to higher values (*Fig. 1*). These slight deviations, different in gneiss and massive metabasite units (*Table 1*), were taken into account by transferring the electrofacies to the logs of the KTB-HB.

Results

Similar to the pilot hole the drilling interval down to 3 km of the KTB-HB revealed a succession of gneisses alternating with metabasites and some minor intercalations of calc-silicates all crosscutted by younger lamprophyric and aplitic dykes. After different stages of metamorphism with major overprint under amphibolite facies conditions a deformation in the brittle field resulted in the formation of abundant, often graphite-bearing cataclasites (LICH 1992). Considering all relations between the rocks penetrated and the tool responses known from the KTB-VB, a detailed EFA-LOG was established for the upper 3 km of the KTB-HB (*Fig. 3-12*). Although much less logging data were available it was possible to transfer 16 of 37 calibrated electrofacies as well as to identify hitherto unobserved lithotypes. The typical lithological characteristics of the applied electrofacies defined for gneisses and amphibolites are summarized in *Table 2*.

GNEISSES:	
IIb	biotite potassium feldspar gneiss + graphite, ore minerals and radioactive accessories
IIIa	hornblende garnet biotite gneiss
IIIb	(hornblende) biotite gneiss with higher proportions of potassium feldspar
IVa-h	alumino-silicate-bearing paragneisses
IVa	phyllosilicate-rich
IVb	quartz-rich
IVc	very quartz-rich
	modified by cataclastic overprint
IVd	+ graphite / ore minerals
IVe	+ graphite / ore minerals + potassium feldspar
IVg	+ graphite / ore minerals + radioactive accessories
IVh	faulted or fissured without graphite
VIIa-b	plagioclase-rich gneiss (calc-silicate-bearing)
VIIa	+ radioactive accessoires
AMPHIBOLITES:	
3a,d,e	garnet-bearing massive amphibolites
3b	calc-silicate-bearing amphibolite
3f	amphibolite which leads to hornblende gneisses

Table 2: Lithological characteristics of all applied electrofacies for gneissic and amphibolitic rocks establishing the EFA-LOG *in the upper 3000 m of the KTB-HB.*

In accordance with the cuttings profile the EFA-LOG is divided into six larger lithostratigraphic sequences. Down to 520 m the logs reflect a heterogenic, partly strong cataclastic overprinted gneiss/metabasite alternation (*Fig. 3*). In this section the maximum values of the upper 3 km KTB-HB were recorded by the NGS. Besides the main rock types of massive amphibolites (3a,d,e), paragneisses (IVa-c) and hornblende gneisses (IIIa) also varieties like calc-silicate amphibolites (3b) and (hornblende) gneisses (IIIb) with high contents of potassium feldspar are separated in the EFA-LOG. Various cataclastic rock types all characterized by low measured resistivities could also be distinguished.

Between 520 - 1180 m, 1410 - 2375 m and 2700 to 3000 m more or less homogeneous successions of alumino-silicate-bearing paragneisses were drilled trough. In the paragneiss units the recorded gamma ray, as well as density and neutron porosity, is clearly dependent on the quartz/phyllosilicate ratio of the rocks. This was shown by HAVERKAMP & WOHLENBERG (1991) for paragneisses of the KTB-VB. Based on this experience also the paragneiss successions of the KTB-HB could be divided into alternations of quartz- and phyllosilicate rich varieties by using the logs. The observed mineralogical and physical differences of the gneisses may be related to their sedimentary educts in so far that quartz-rich lithotypes (IVb/IVc) are products of greywackes whereas the phyllosilicate-rich type (IV) with higher gamma activity and density is formed from more clayey sediments. Plagioclase-rich gneisses, unknown in the KTB-VB, were identified by their characteristic low potassium contents. For this rocktype, drilled through between 950 and 980 m (*Fig. 5*), two electrofacies were distinguished by the logs; lithotype VIIa is characterized by higher thorium contents than the lithotype VIIb.

Most of the metabasic rocks are related to two larger lithostratigraphic units, different in origin and material composition. The massive metabasite sequence (1180 to 1410 m, *Fig. 6*), sharply separated from the paragneisses by significant low gamma activity, is derived from mafic intrusives (PATZAK et al. 1991). This sequence is mainly composed of amphibolites with intercalated metagabbros which are more abundant in the EFA-LOG than in the cuttings profile. Differentation of the metagabbros, distinguished in the almost completely cored KTB-VB by relict magmatic fabrics, was not always possible by analysing the cuttings samples of the KTB-HB (see GODIZART et al. 1991). Applying the calibrated electrofacies to the KTB-HB it was possible to distinguish the more mafic metagabbros by characteristic low gamma activity as well as the amphibolite variety 3f which leads to gneissic rocks. The second mafic lithostratigraphic unit, a heterogeneous gneiss/amphibolite succession, was drilled through between 2375 - 2700 m (*Fig. 10*). Similar to the unit down to 520 m this sequence is probably derived from volcanic rocks and intercalated sediments (PATZAK et al. 1991). According to the strong variations of the recorded log responses the EFA-LOG shows a detailed alternation of hornblende gneisses, amphibolites and alumino-silicate-bearing paragneisses. Furthermore the lithotype amphibolite gneiss was distinguished by the logs as a linkage between gneissic and amphibolitic rocks.

Besides the discrimant electrofacies also the relations between various logs, often specific for the main lithological units were found suitable for establishing an EFA-LOG even when less data were available. Especially the TH/U as well as the SGR/POTA-ratios are important. *Figure 2* shows the typical pattern of the main lithological groups in the cross-plot SGR versus POTA. Despite overlapping NGS-logging responses the three distinguished gneiss groups (alumino-silicate-bearing paragneisses, plagioclase-rich gneisses and hornblende gneisess) can clearly be separated by different SGR/POTA ratios. In general, the following trends can be derived from the calculated average ratios of the main lithological units: The SGR/POTA ratio decreases from acid to mafic rocks whereas the THOR/URAN ratios are significant higher in the massive amphibolites and metagabbros than in the gneissic rocks (*Table 3*).

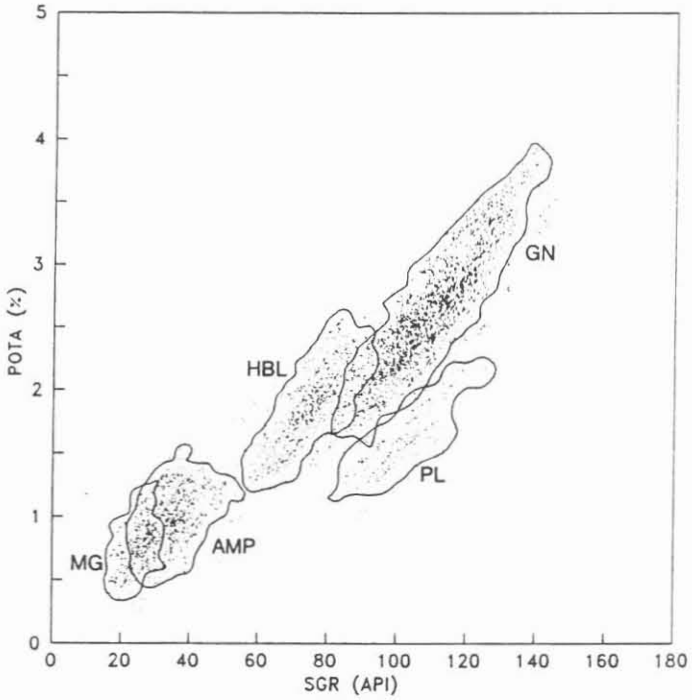


Fig. 2: Cross-plot SGR versus POTA with the typical distribution of the main lithological units which are distinguished in the EFA-LOG.*- GN: alumino-silicate-bearing paragneisses, HBL: hornblende gneisses, PL: plagioclase-rich gneisses, AMP: amphibolites, MG: metagabbros.*

	plagioclase rich gneiss	alumo silicate paragneiss	hornblende gneiss	amphibolite	metagabbro
THOR/URAN	3.40	2.81	2.56	5.49	4.39
SGR/POTA	64.35	43.73	40.48	36.66	33.64

Table 3: Average values of the SGR/POTA and THOR/URAN ratios for the main lithological units calculated from the first 3000 m of the KTB-HB.

Considering the results presented the following can be concluded:
Based on a careful quality control, the application of calibrated electrofacies from one well to another is possible also in crystalline rocks, assuming more or less similar lithologies. Even in the case of meagre available logging data, a detailed synthetic profile of the drilled lithology can be established with this applied method. The high sampling rate of borehole measurements provides not only better depth resolution than analysis of cuttings but also better differentiation of the lithological units. To this extent the EFA-LOG should be used as an additional tool for special geological objectives, such as questions related to lithostratigraphy and tectonic features or for detailed correlation of the KTB-VB with the KTB-HB.

Following pages:
Fig. 3-11: Comparision of EFA-LOG *and cuttings profile for the depth interval 280 - 3000 m KTB-HB. In the* EFA-LOG *the main lithological groups are marked in the left column; their varieties in the right column.*
The depth of the cuttings profile is related to lag time.

References

GODIZART, G., GLEIß, N., HANSMANN, J., HÄUSSINGER, H., KEYSSNER, S., KOHL, J. & LAPP, M. (1991): Tiefbohrung KTB-Oberpfalz HB, Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor (Windischeschenbach), Teufenbereich von 0 bis 1720 m: B. Geologie.- In: Emmermann, R., Dietrich, H.-G., Lauterjung, J. & Wöhrl, Th. (Hrsg.): KTB-Report **91.3**: Hannover.

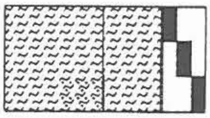
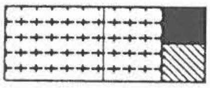
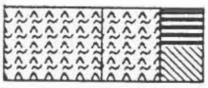
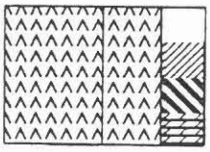
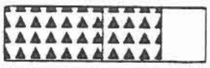
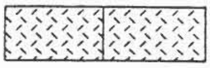
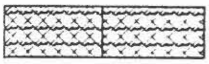
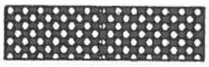
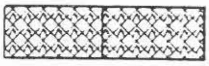
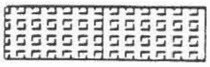
HAVERKAMP, S. & WOHLENBERG, J. (1991): EFA-LOG - Rekonstruktion kristalliner Lithologie anhand von bohrlochgeophysikalischen Messungen für die Bohrungen Urach 3 und KTB-Oberpfalz VB.- KTB-Report **91-4**: Stuttgart (Schweizerbart'sche Verlagsbuchhandlung).

LICH, S., DUYSTER, J., GODIZART, G., KEYSSNER, S. & WALL, H., de (1992): German Continental Deep Drilling Program (KTB) - geological survey of the Hauptbohrung 0-6000 m: B. Geologie.- In: Emmermann, R., Dietrich, H.-G., Lauterjung, J. & Wöhrl, Th. (Hrsg.): KTB-Report **92.2**: Hannover.

PATZAK, M., OKRUSCH, M. & RÖHR, C. (1991): Die Metabasite der KTB-Vorbohrung: Petrographie, Geochemie, Mineralchemie und Metamorphoseentwicklung. - In: Emmermann, R. & Lauterjung, J. (eds.): Forschungsergebnisse im Rahmen des DFG-Schwerpunktprogrammes "KTB", 1986 - 1990. - KTB Report **91-1,** 63-82, Hannover.

We would like to express our thanks to the well logging group of the KTB-Project and to the field laboratory, for providing the digitized cuttings profile, geochemical, petrograpical, and petrophysical data.

LEGEND

CUTTINGS-PROFILE		EFA-LOG	
paragneiss: gnt-sil-bio-gneiss mus-bio-gneiss		IVa IVb IVc	paragneiss (alumo silicate bearing)
plagioclase rich gneiss		IIVa IIVb	plagioclase rich gneiss
hornblende gneiss		IIIa IIIb	hornblende gneiss
amphibolite		3a,d,e 3b 3f	amphibolite amphibolite gneiss
metagabbro			metagabbro
lamprophyre			lamprophyre
cataclastic gneiss		IVd-h	cataclastic gneiss
cataclasite			cataclasite
cataclastic amphibolite			cataclastic amphibolite
alternation gneiss/amphibolite			
calcsilicate rock			

ccc: graphite
◆: pyrrhotine

x: quartz-vein
*: pyrite

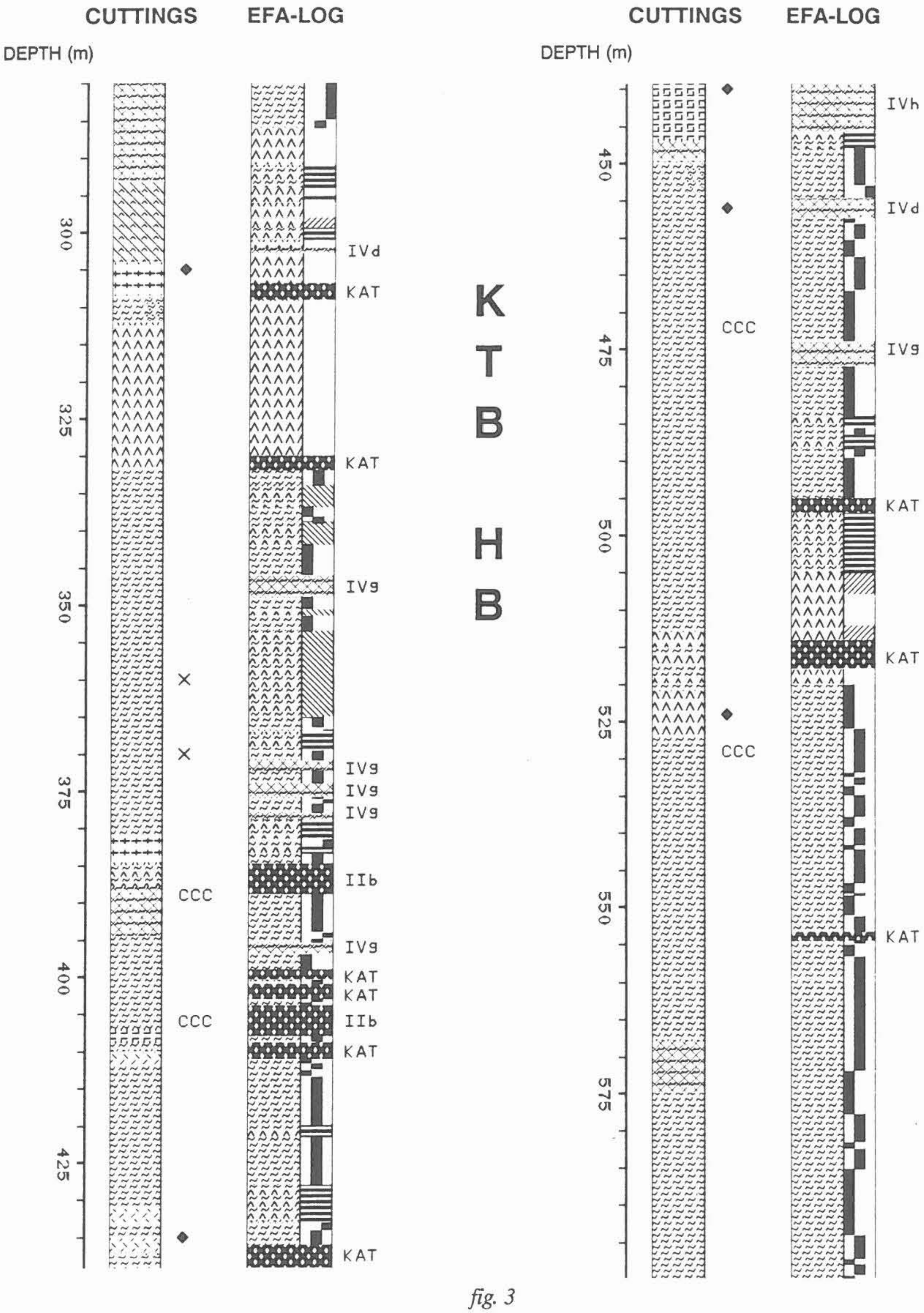

CUTTINGS
EFA-LOG
DEPTH (m)
300
325
350
375
400
425
IVd
KAT
KAT
IVg
IVg
IVg
IVg
IIb
IVg
KAT
KAT
IIb
KAT
KAT
CCC
CCC
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
450
475
500
525
550
575
IVh
IVd
CCC
IVg
KAT
KAT
CCC
KAT

fig. 3

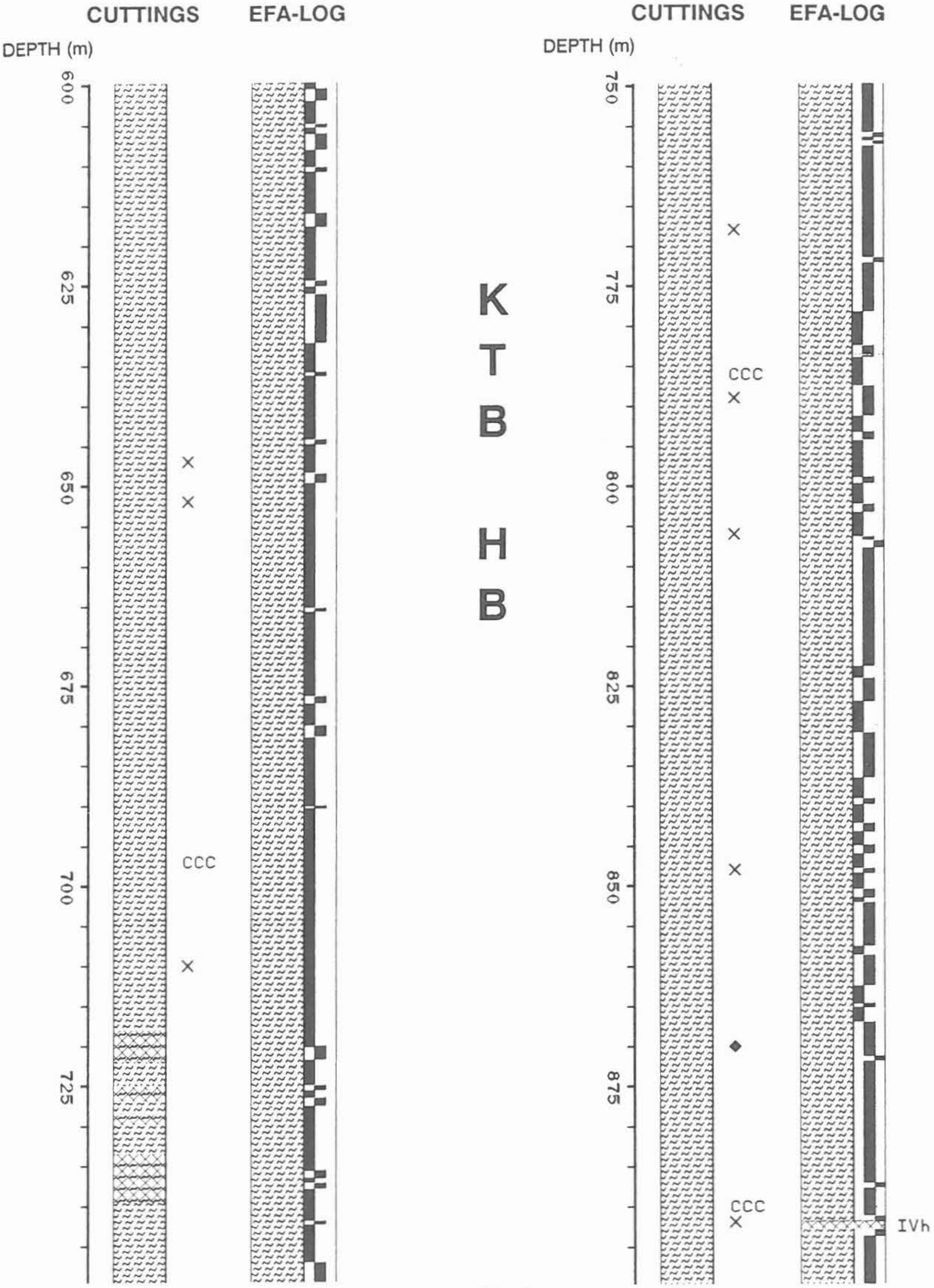

CUTTINGS
EFA-LOG
DEPTH (m)
600
625
650
675
700
725
×
×
CCC
×
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
750
775
800
825
850
875
×
CCC
×
×
×
◆
CCC
×
IVh

fig. 4

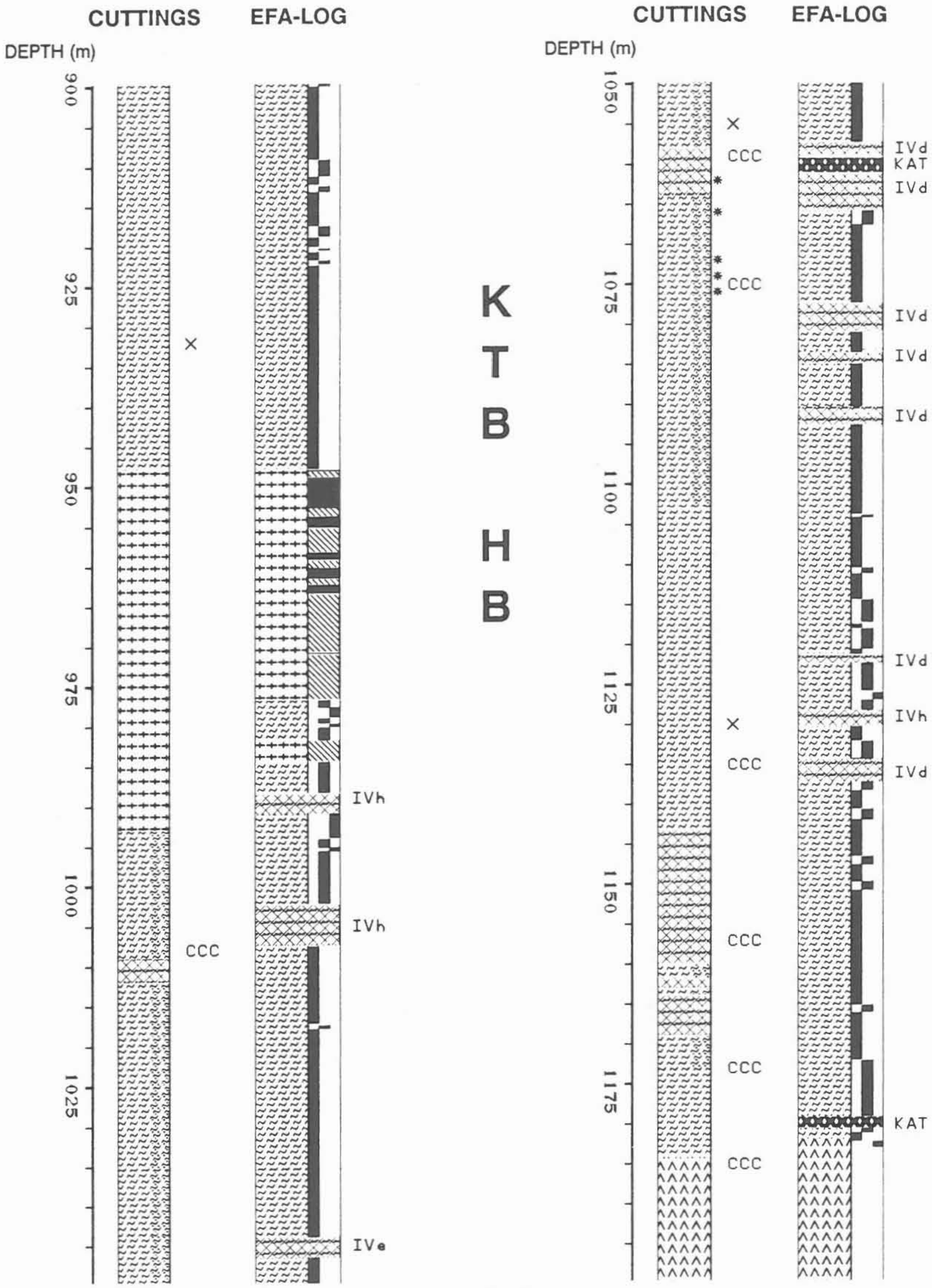

CUTTINGS
EFA-LOG
DEPTH (m)
900
925
950
975
1000
1025
×
CCC
IVh
IVh
IVe
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
1050
1075
1100
1125
1150
1175
×
CCC
CCC
×
CCC
CCC
CCC
CCC
IVd
KAT
IVd
IVd
IVd
IVd
IVd
IVh
IVd
KAT

fig. 5

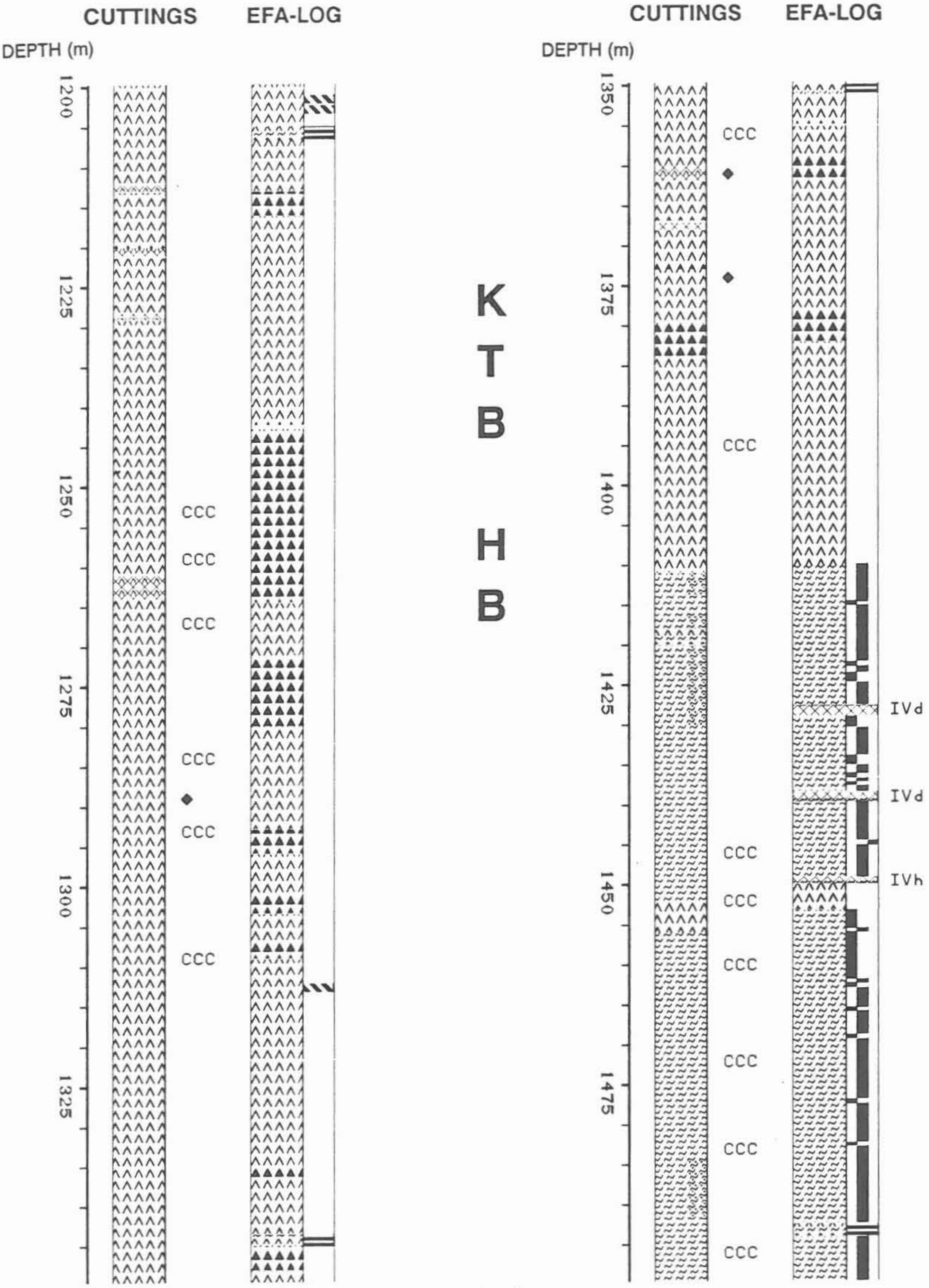

CUTTINGS
EFA-LOG
DEPTH (m)
1200
1225
1250
1275
1300
1325
CCC
CCC
CCC
CCC
CCC
CCC
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
1350
1375
1400
1425
1450
1475
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
IVd
IVd
IVh

fig. 6

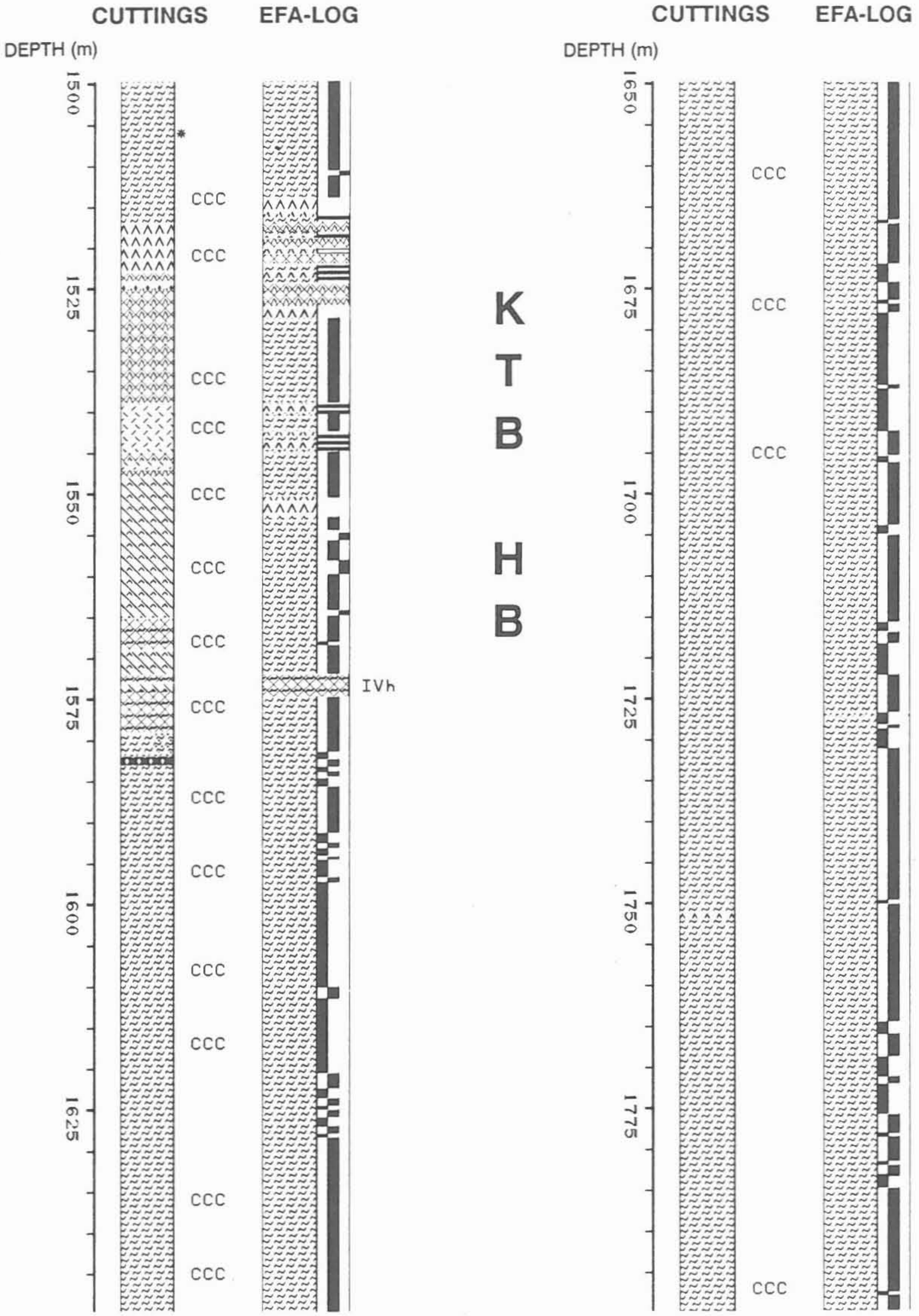

CUTTINGS
EFA-LOG
DEPTH (m)
1500
1525
1550
1575
1600
1625
*
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
CCC
IVh
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
1650
1675
1700
1725
1750
1775
CCC
CCC
CCC
CCC

fig. 7

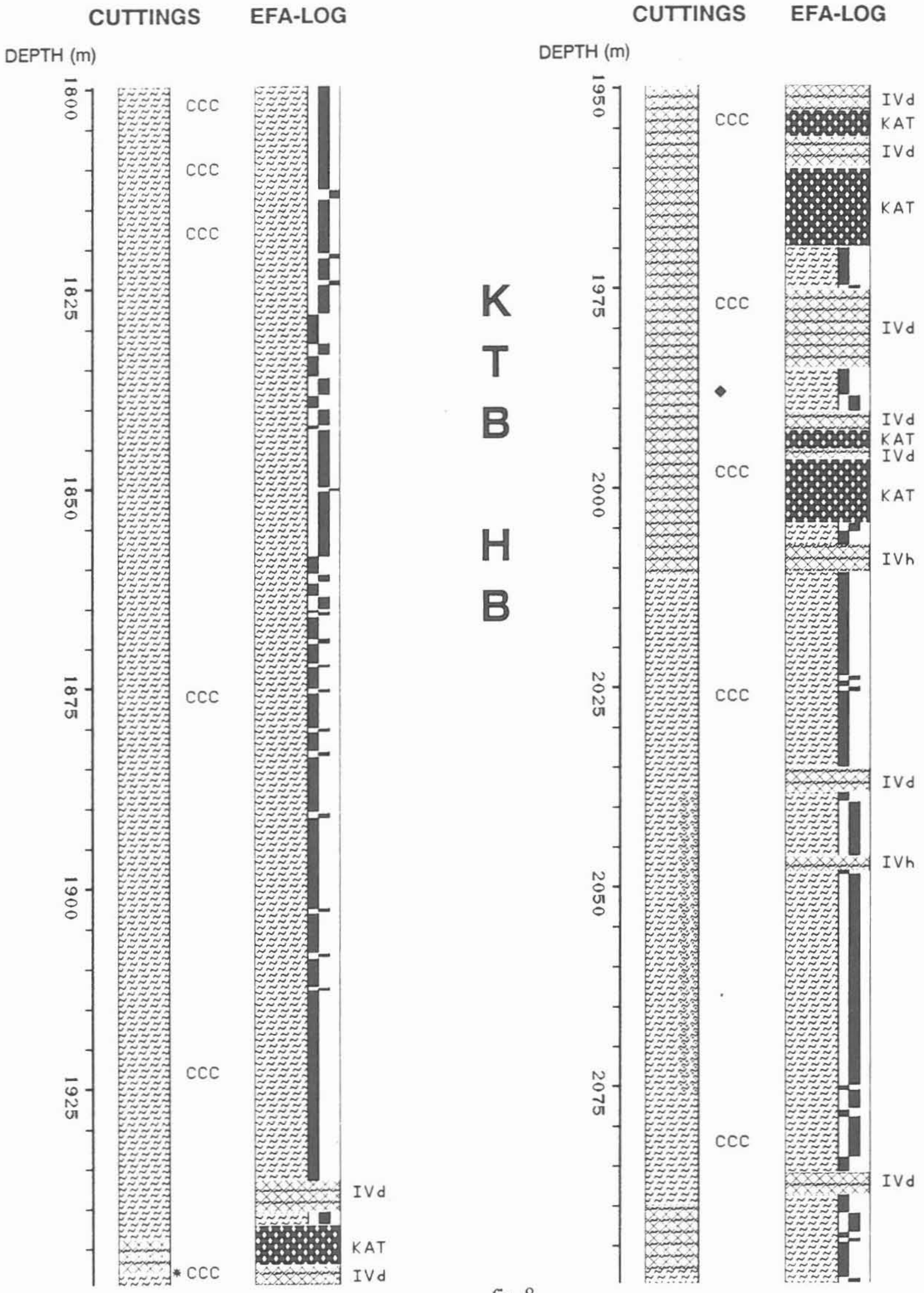

CUTTINGS
EFA-LOG
DEPTH (m)
1800
1825
1850
1875
1900
1925
CCC
CCC
CCC
CCC
CCC
* CCC
IVd
KAT
IVd
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
1950
1975
2000
2025
2050
2075
CCC
CCC
CCC
CCC
CCC
IVd
KAT
IVd
KAT
IVd
IVd
KAT
IVd
KAT
IVh
IVd
IVh
IVd

fig. 8

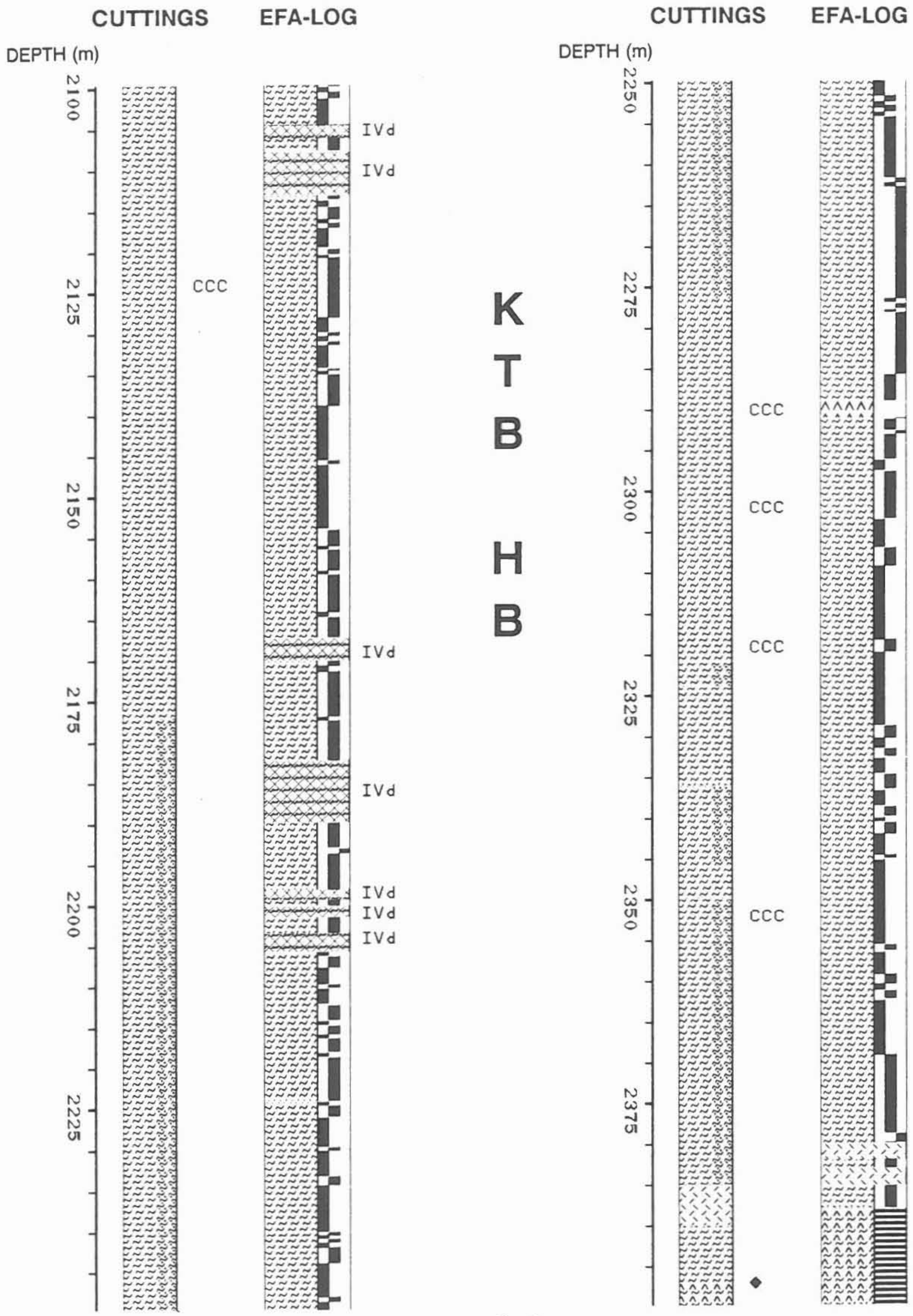

CUTTINGS
EFA-LOG
DEPTH (m)
2100
2125
2150
2175
2200
2225
IVd
IVd
CCC
IVd
IVd
IVd
IVd
IVd
KTB HB
CUTTINGS
EFA-LOG
DEPTH (m)
2250
2275
2300
2325
2350
2375
CCC
CCC
CCC
CCC

fig. 9

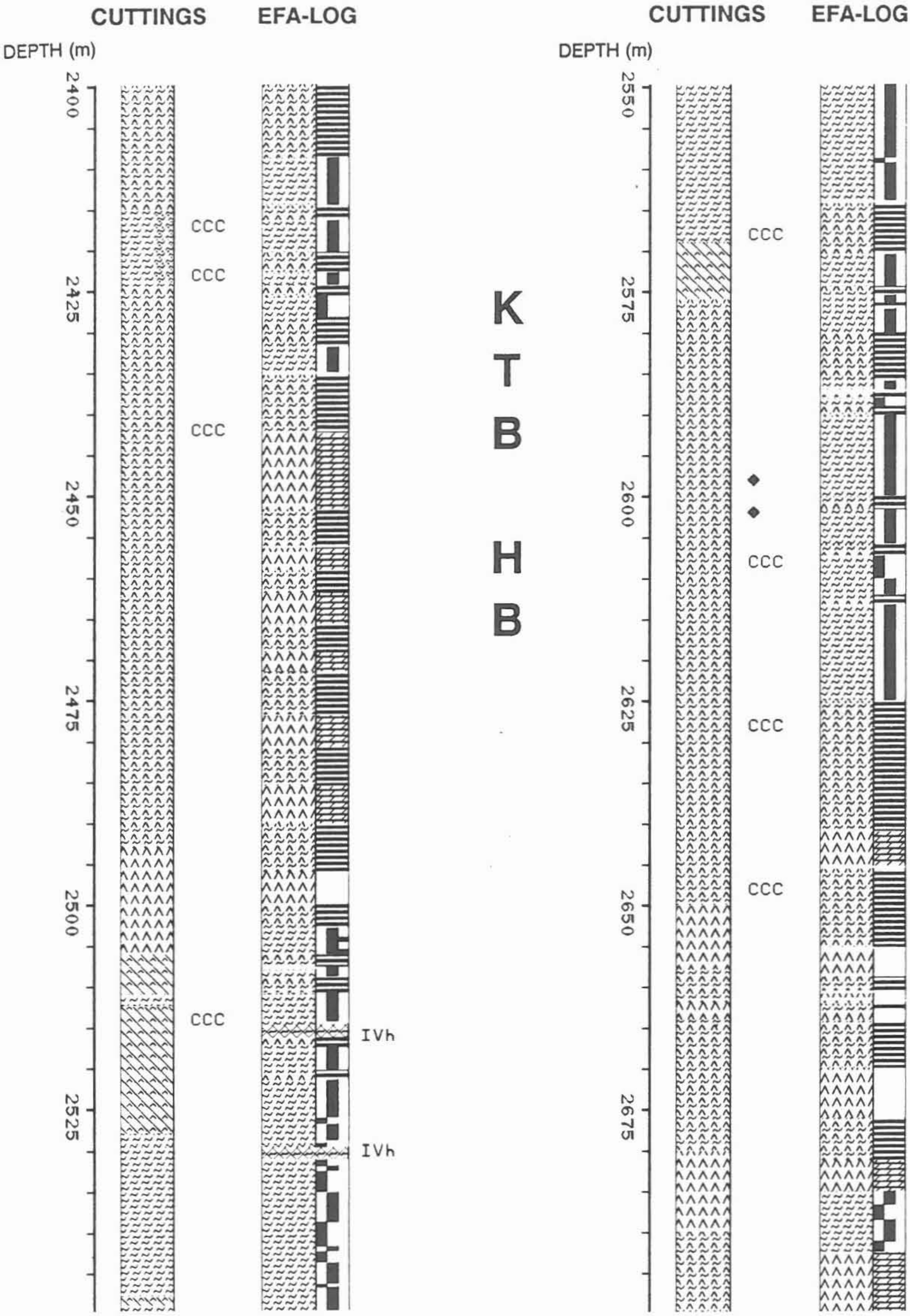

CUTTINGS
EFA-LOG
DEPTH (m)
2400
2425
2450
2475
2500
2525
CCC
CCC
CCC
CCC
IVh
IVh
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
2550
2575
2600
2625
2650
2675
CCC
CCC
CCC
CCC

fig. 10

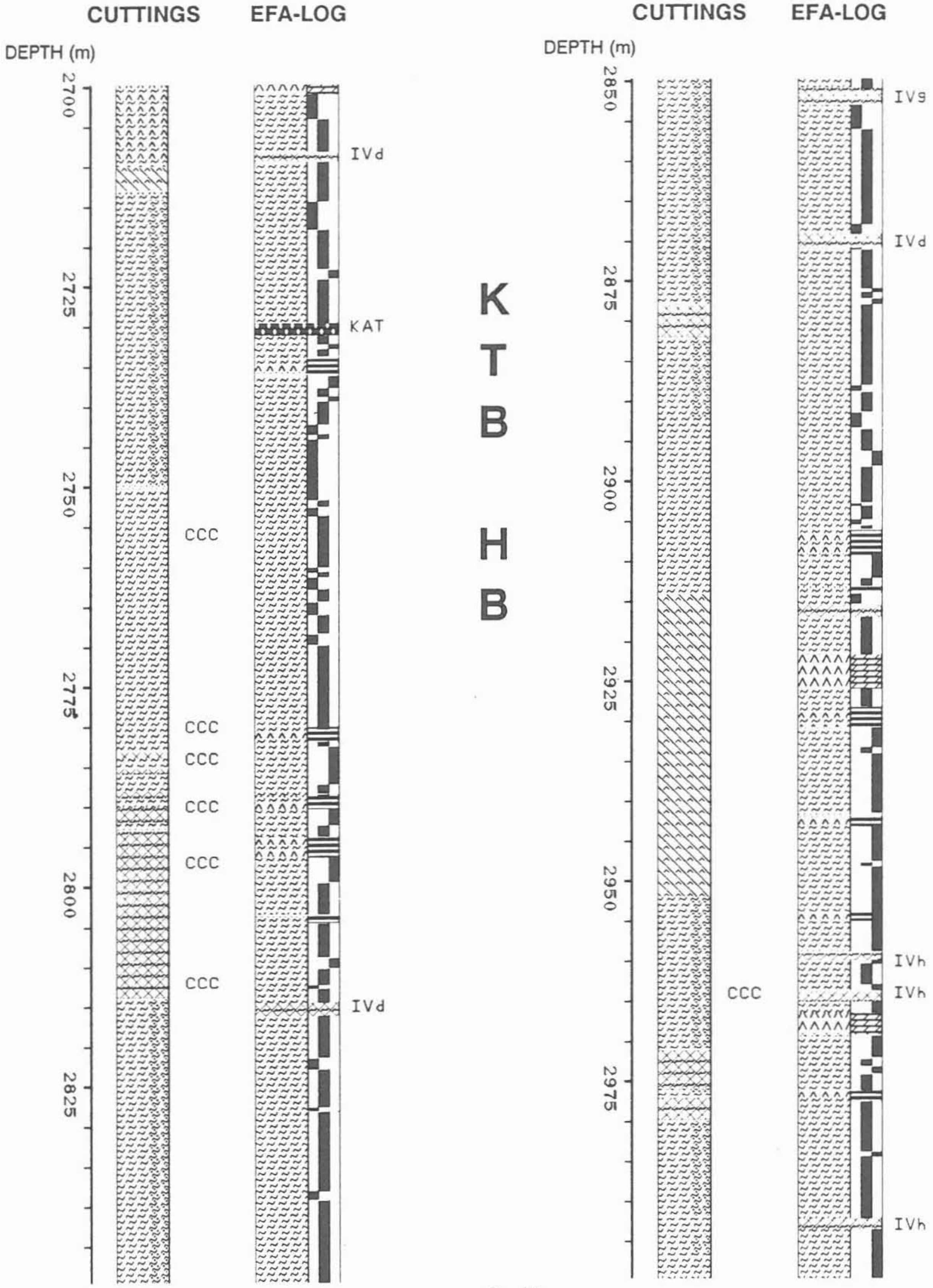

CUTTINGS
EFA-LOG
DEPTH (m)
2700
2725
2750
2775
2800
2825
CCC
CCC
CCC
CCC
CCC
CCC
IVd
KAT
IVd
K
T
B
H
B
CUTTINGS
EFA-LOG
DEPTH (m)
2850
2875
2900
2925
2950
2975
IVg
IVd
CCC
IVh
IVh
IVh

fig. 11