Crosshole seismic imaging of a fractured reservoir
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Introduction
Time-lapse crosshole seismic surveys have been conducted over a naturally fractured reservoir to demonstrate the feasibility of obtaining high-resolution seismic images to monitor changing fluid saturation within the reservoir. The experiment was performed at the Chalmers Hot Dry Rock (HDR) geothermal research site in Fjällbacka, Sweden, across a fractured reservoir. In crystalline rock at around 450 m depth. Although the survey technique being demonstrated is intended to be applied to oil reservoirs, the Fjällbacka site was selected as the geothermal reservoir there is analogous to a naturally fractured oilfield reservoir but is far more readily accessible for experimental work.

The objective of the HDR research at Fjällbacka was to stimulate the natural fractures and develop a high permeability fractured reservoir for heat exchange. Hydraulic interference tests conducted across the reservoir had identified a high flow impedance, suggesting that the permeable fractures at the boreholes are not well connected between the boreholes. The objective of the crosshole seismic surveys was to image the permeable fractures in the reservoir to obtain a direct indication of the connectivity between the boreholes.

Crosshole data acquisition involves deploying a source in one well and detecting it at one or more receivers in a second well. From observations of the traveltimes along crosshole ray paths an image of the velocity in the interwell region may be formed using a technique known as transmission tomography (Bois \textit{et al.}, 1971). Interpretation of toigrams can provide a detailed image of geological features, such as fracture zones (Wong \textit{et al.}, 1983; Ramirez, 1986) and faults (Lines, 1991). The method is also particularly well suited to monitoring changes due to downhole treatments such as reservoir flooding in enhanced oil recovery procedures (Justice \textit{et al.}, 1989; Mathisen \textit{et al.}, 1995).

Crosshole seismic techniques have the potential to provide an order of magnitude greater resolution than equivalent surface seismic techniques due to the higher frequencies which can be employed. Typically resolution of the order of several metres can be expected from transmission toigrams, utilizing frequencies of 1 kHz or more, which enables significantly more detailed interpretations of the interwell region to be made than from surface seismic or VSP.

None the less, it is now well established that transmission toigrams may contain a variety of artefacts due to, for example, ray coverage (Dyer and Worthington, 1988) and anisotropy (McCann \textit{et al.}, 1989; Pratt \textit{et al.}, 1993). Transmission toigrams also present a smoothed image of the velocity field. In an effort to improve upon the resolution of transmission toigrams, and in particular to achieve better resolution of edges, crosshole wavefield imaging techniques have been developed (Findlay \textit{et al.}, 1991; Pratt and Goulty, 1991; Rector \textit{et al.}, 1994; Rowbotham and Goulty, 1994; Tura \textit{et al.}, 1994). To apply the wavefield techniques, direct arrivals and noise events, such as tube waves, need to be eliminated. Successful separation of the desired wavefield requires a high density of source and receiver locations to prevent aliasing in the processing. However, it is only with the development of efficient borehole sources in the last few years that the acquisition of crosshole datasets in oilfields has become a practical proposition (Harris \textit{et al.}, 1995; Lee \textit{et al.}, 1995).

In this paper we present high-resolution crosshole data, acquired with a downhole sparker seismic source (Dyer and Baria, 1995) and a string of hydrophone receivers. Two surveys were conducted, the first at the ambient borehole pressure and the second at an elevated downhole pressure of 3.35 MPa to inflate the reservoir. From both the ambient and pressurized data sets P-wave toigrams and reflection images were formed. In order to maximize the resolution of zones of increased fluid saturation (fracture opening) due to the pressurization, difference images were formed by subtracting the ambient and pressurized toigrams and wavefield images.

Method
Site description
The experiments were carried out at the Fjällbacka borehole test site on the Swedish west coast, about 150 km north of Göteborg. This site was established in 1984 as an \textit{in situ} research facility for studying geological, hydrogeological and hydromechanical aspects of HDR geothermal reservoir devel-
Porphyritic granite and (b) red medium-to-coarse-grained granite with low contents of biotite and other mafic phases. The crosshole surveys were performed between FJB1 and FJB3 over a depth range of 400-480 m. The corresponding lithological profiles are shown in Fig. 2.

The natural fracture system is dominated by two almost orthogonal subvertical sets and one sub-horizontal set creating a pattern of approximately rectangular blocks. The horizontal stresses appear to be larger than the vertical stress to at least 450-500 m depth, thereby favouring the opening of horizontal fractures during pressurization.

During and after the drilling of the wells, hydraulic tests and thermal and hydrochemical logging provided information on hydraulically active fractures and fracture zones. In FJB1, falling head injection tests were carried out in 6 m-long straddled sections from 200 m to 500 m depth. Notably, all fractures accepting water were horizontal or sub-horizontal, dipping less than 20°. The permeability of conductive zones were typically in the range $10^{-18}$-$10^{-15}$ m$^2$ (1 μD to 1 mD).

In November 1986, a viscous fluid stimulation experiment was carried out in well FJB1. The stimulation was primarily aimed at creating a high-permeability heat exchange area at 450 m depth, suitable for water circulation and heat extraction experiments. The target radius for the fracturing operation was 150 m and the operational parameters were selected on the basis of earlier experience and predictions from conventional hydraulic fracture models. During the stimulation, passive microseismic monitoring was used to follow the distribution of...
pore pressure increase and fluid flow (Wallroth et al., 1996). Subsequently, to evaluate the results of the stimulation, single-hole packer tests were carried out at the level of the stimulation in FJB1. These tests indicated a permeability increase from $10^{-17}$ m$^2$ (10 μD) before the stimulation to $10^{-14}$ m$^2$ (10 mD) after the stimulation.

Based on the tectonic and hydraulic information and the distribution of induced microseismicity, which was assumed to indicate regions of increased permeability, a second 500 m deep inclined well, FJB3, was drilled into a dense area of microseismicity at a lateral distance from FJB1 of 100 m (Fig. 3). The well intersected a high permeability zone at the expected depth and horizontal position predicted from the microseismicity. Remnants of viscous gel were encountered whilst drilling through the microseismic zone, which confirmed a hydraulic connection to FJB1. The local transmissivity of this zone was about four orders of magnitude higher than transmissivity measured elsewhere in the well.

During the hydraulic stimulation carried out at 450 m depth in well FJB1 a total of 72 induced seismic events were detected. A subsequent open-loop hydraulic circulation produced several hundred induced events, distributed up to 500 m from the injection well. One of the most interesting observations during this experiment was the occurrence of extensive seismic activity at injection pressures at least 2 MPa below the fluid pressure required to overcome the minimum effective principal stress and produce fracturing of the horizontal fractures. Focal mechanism analysis in conjunction with rock mechanical modeling, using a simple peak shear strength concept, and the in-situ stress data found that reservoir growth during fluid injection took place through the shear failure of shallowly dipping fractures.

The microseismic data detected during the stimulation of FJB1 provides compelling evidence of a link between induced seismic activity and fluid flow. Furthermore, the strongly anomalous permeability measured in FJB3 within the zone of seismicity may be taken as an indication that shearing has induced an increase in permeability up to at least 100 m from the injection well.

All the available borehole data are summarized schematically in Fig. 2. The permeability, number of fractures/m and lithology were derived from the experimental work described above. The locations of tube wave generating features, which are discussed later, are also shown. These borehole data have also been plotted without detailed annotation alongside subsequent tomograms and wavefield plots to enable borehole and seismic image features to be correlated.

**Inflation of the reservoir**

The experimental programme was designed to obtain two crosshole seismic data sets, the first at ambient pressure and the second at an elevated downhole pressure. Both crosshole seismic surveys were performed at Fjällbacka between 5 and 23 June 1995. During both surveys the sparkers were deployed in borehole FJB3 which dips at around 80° to the horizontal and the hydrophone string was deployed in borehole FJB1 which is near vertical. The survey depth range was between 400 m and 480 m beneath ground level. Both the sparkers and string of four hydrophones were deployed on standard seven core wireline logging cable.

The pressurized survey was performed at an overpressure of 3.2-3.4 MPa. Inflatable packers (Lyens PIP 5 3/8") were deployed on 2 7/8" tubing to isolate the test sections of the boreholes below 350 m depth. The packers were inflated with water from the surface through reinforced hydraulic hoses. Pack off assemblies were fitted on the top of both pipe strings to seal between the cables and the inside of the tubing. The construction of the pack-off assemblies permitted the tools to be moved in the boreholes under pressurized conditions.

The packed off region, below 350 m, was pressurized by pumping water into the tubing at FJB3. Well FJB1 was kept open during the first few hours of injection in order to observe the production flow out of the well. Thereafter the valve at the

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**Fig. 3** View from the south of the microseismicity induced during the FJB1 stimulation and subsequent circulation trials. NB this is the same view as the seismic sections.
The injection pressure was monitored close to the top of FJB3. The pressurized crosshole survey began at 3.2 MPa and pumping continued throughout the survey to maintain the pressure. Over the 12 and a half hours of the survey the pressure rose only a little to 3.35 MPa suggesting that the system was close to equilibrium throughout the survey.

Seismic data acquisition

The same acquisition parameters were used for both surveys so that the seismic data could be directly compared. A source interval of 1 m was selected which gave a good spatial coverage. The receiver interval, 1.7 m, was the minimum physical separation which could be obtained between hydrophones in the string. Although a smaller receiver interval could have been achieved by moving the hydrophone string by a fraction of the receiver spacing this would have entailed firing the source a greater number of times in proportion to the reduction in receiver spacing. This would have been impractical in the time available.

The source and receiver locations are shown in Fig. 2. These locations are numbered from 0 at the deepest locations up to 80 for the top source location and 43 for the top receiver location. This numbering is consistent with the direction in which the tools were moved during the surveys which was from bottom to top, the conventional wireline logging procedure.

A sample interval of 0.1 ms was used, which was more than five times the typical Nyquist frequency of the recorded wavefield and a record length of 200 ms which was sufficient to acquire all possible direct arrivals and reflection events. Only an anti-alias filter was applied to the raw data prior to recording. The bandwidth of the hydrophone system extended from a few Hz to 4 kHz which is more than sufficient to detect the typical free field source frequency of around 1700 Hz (Dyer and Baria, 1995).

For each location of the hydrophone string a single shot at each source location was fired in turn. The time interval between shots from the sparker was 25 s which provided sufficient time to record the seismic traces and to move up to the next source location. In this way the data could be acquired very efficiently. Each complete source run of 81 source locations could be completed in around an hour including returning the sparker to the bottom of the survey range and moving the hydrophone string to the next location ready for the next source run. Using this acquisition procedure the pressurized survey, which is equivalent to frequencies of 1550-1650 Hz.

Shear wave arrivals are not present over much of the data due to the limited angular range of the ray coverage. The radiation pattern of the sparker is equivalent to a point source in a borehole (Dyer and Baria, 1995). This type of source produces strong P-wave energy perpendicular to the borehole and up to 50° away from the perpendicular. In contrast S-wave energy is predominantly produced at angles of around 45° to the perpendicular and there is no S-wave energy perpendicular to the borehole. The highest angle ray paths lie between the shallowest receiver in FJB1 and deepest source locations in FJB3. Due to a tube wave arrival the shear wave is best seen on receiver gather 41 (Fig. 4), which is two locations below the shallowest receiver.

There are a number of tube wave arrivals in the data. Tube waves may be generated by the source or by incident body waves upon features in the borehole such as open fractures intersecting the borehole, changes in borehole diameter and lithological boundaries. Consequently a variety of single and multiple combinations of tube wave to body wave conversions may combine to form a path between sources and receivers. The principal tube wave paths observed in these data are shown schematically in Fig. 5 and were as follows:

Type 1 Source generated tube wave converted to a P-wave at a discontinuity in the source well and detected as a P-wave in the receiver well.

Type 2 Source generated P-wave converted to a tube wave at a discontinuity in the receiver well and detected as a tube wave.

RESULTS

Raw seismic data analysis

A typical receiver gather collected at a receiver depth of 408 m during the unpressurized survey is shown in Fig. 4. The data shown are the raw unstacked and unfiltered traces as recorded in the field. There is a good signal-to-noise ratio, typically greater than 10 for the direct P-wave arrivals. The period of the P-wave arrivals varied between 0.60 and 0.65 ms over the data set, which is equivalent to frequencies of 1550-1650 Hz.

Fig. 4 Receiver gather at a depth of 408 m collected during the unpressurized survey. The S-wave lies between 38 ms at source 0 and 30 ms at source 40. Global scaling. Time in ms.
Type 3 Source generated tube wave converted to a P-wave at a discontinuity in the source well, radiated as a P-wave, converted to a tube wave at a discontinuity in the receiver well and detected as a tube wave. [N.B. No tube wave to shear wave or shear wave to tube wave conversions were observed in these data although these conversions are possible.]

The tube waves in the data fall into two distinct groups, those with large amplitudes and those with small amplitudes. The depths at which large and small amplitude tube waves originated are denoted by long and short lines, respectively, in the borehole data plots.

Transmission tomographic processing

Velocity images of the survey region were formed using a ray theoretical tomographic technique. The method involves forming an image of the velocity over the region of the survey from observations of the travel times of the seismic waves. The unpressurized and pressurized survey tomograms were very similar and so only the unpressurized tomogram is illustrated (Fig. 6) for brevity.

Picking the P-wave travel times was straightforward due to the high frequencies and good signal-to-noise ratio of the data. The picking was performed on the raw data for both the pressurized and unpressurized surveys. Frequency filtering of the data was not used as it was unnecessary and produces phase shifts which could have caused a shift in the travel time picks.

Potential picking and trigger errors were thought to be ±1 sample, 0.1 ms, which is equivalent to a distance error of ±0.5 m or an error of ±0.5% in the average velocity along a typical ray. In comparison the expected random depth errors were ±0.1 m. In view of the averaging effect of the very high number of travel time observations contributing to the image, these random travel time and depth errors are thought to be insignificant.

The accuracy of the borehole surveys, from which the 3D locations of the sources and receivers were calculated, is difficult to estimate. However, the boreholes are quite straight and so only small location errors were expected, perhaps less than 1 m. Such errors would have some effect on the absolute values of the imaged velocities but would not be expected to significantly affect the velocity distribution.

Straight rays were used to form the images. The maximum variation in the imaged velocities was little more than 10% for which the straight ray approximation was considered to be reasonable. The images were formed using 20 iterations of an iterative reconstruction technique known as the Simultaneous Iterative Reconstruction Technique (SIRT) in which the L2 (least squares) norm was minimized (Dines and Lyttle, 1979). No constraints were applied during the imaging to control or limit the imaged velocities.

Choosing the cell size is a balance between using a small size to obtain greater potential resolution whilst using a size large enough to be properly resolved by the available ray density and coverage. According to Williamson (1991) the resolution of ray tomography is approximately equal to the first Fresnel zone radius given by \( \sqrt{\lambda L} \). The wavelength (\( \lambda \)) of the direct P-wave was around 3.5 m. Taking the scale length, \( L \), as 50 m at the centre of the survey region, gives a resolution of around 13 m. To adequately sample a feature of this size a cell size of 5 m square was initially selected.

Tests were also performed using a cell size of 2.5 m square which produced a very similar velocity distribution but the image was more noisy due to the reduced ray coverage and ray density within each cell. The fit of the observed travel times to the calculated times improved very little using the smaller cell size indicating that the resolution was not as fine as 2.5 m and that 5 m was a suitable cell size to have used.
Over all the ray paths the root mean square difference between the observed travel times and the times through the velocity images was 0.05 ms which is half the sample interval. This indicates that the images were a very good fit to the data. The distribution of errors can be assessed from a contour plot of the error for each source/receiver pair. This type of error plot for the unpressurized tomogram is shown in Fig. 7. Most of the errors are $\pm 0.1$ ms. The white gaps in the error plot are due to a few missing traces where there were no travel time picks.

There is a tendency for the travel time errors to be aligned along receiver gathers and, to a lesser extent, along shot gathers producing faint stripes in the plot. The amplitude of the variation between the stripes is consistent with the sample interval which suggests that the stripes reflect the picking resolution which was one sample. The alignments are not due to receiver depth errors as they are not related to individual locations of the hydrophone string which would produce consistent errors across groups of four receivers.

In both surveys there was a similarly distributed low amplitude and low frequency variation in the errors. These errors were unlikely to be due to depth measurement errors as the polarity of the errors was not consistent in the source or receiver direction. Also the magnitude of the errors suggest an error of around 1 m which is more than expected in the depth measurements. The most likely source of these errors is thought to be inaccuracies in the borehole surveys.

**Wavefield processing**

The objective of the wavefield processing was to obtain pre-stack depth migrations of the crosshole data from which changes in reflectivity due to the pressurization could be identified. The same processing was applied to the traces from the pressurized and unpressurized surveys. No trace or time-dependent scaling of the traces was applied so the trace amplitudes and migration amplitudes of the two surveys were comparable.

The traces were initially band pass filtered from 100 to 3000 Hz to remove low-frequency noise due to pumping during the pressurized survey. The high-frequency cut off removed energy which is occasionally present immediately after the first arrivals, which was thought to be due to resonance of either the source or receiver boreholes.

Velocity filtering, to separate the tube waves, was performed using a median filter. This was preferred to the slant stack method as it causes much less smoothing and spreading of the data in the filter direction and preserves edges in the data. The median filter was very effective in removing tube wave arrivals from the receiver gathers but was not as effective with the shot gathers as the tube wave arrival is spatially aliased in the shot gathers.

The velocity filtering process led to some high-frequency noise in the traces which was removed with a final low pass filter.

It was not necessary to suppress the S-wave as this contained little energy and the arrival of the S-wave was expected to be later than the predicted reflections over most of the data. The P-wave arrival has a similar moveout to a reflection event and may coincide with a reflection event if the reflector passes through either of the boreholes. These factors make it impractical to remove the P-wave arrival by dip filtering.
Some of the smaller features of the tomogram were not included in the model and may also be real. Common features corresponding to the model can be interpreted as being real. The objective of the modelling was to determine if any of the features in the tomograms were due to distortions and which features were real.

The modelling procedure was an iterative process in which progressively more zones of constant velocity, corresponding to velocity features in the real data tomograms, were included in the model until the image obtained from the model data was similar to the real data image. The model was built up progressively, starting with the largest features, in order to find the simplest model which matched the observed tomograms. The technique verifies that the interpretation is consistent with the data but does not prove this is the right solution or the only solution. The final model and tomogram are shown in Fig. 9.

The models were defined using constant velocity zones with boundaries and velocities initially interpreted from the real tomogram. For example, the first feature to be included in the model was the high velocity at the bottom left of the tomograms. Rays were traced through this model, with refractions at the interface between the high velocity and background, using the same source and receiver locations as for the real data. The model travel times were then treated as if they were real data and imaged using straight rays. Based on a comparison of the model tomogram with the real tomogram, the boundaries of the velocity zone and the velocity of the zone were adjusted and the modelling process was repeated to optimize the fit.

After incorporating the velocity zones indicated in Fig. 9, a reasonable match between the principle features of the real and model tomograms was achieved. Hence the velocity features corresponding to the model can be interpreted as being real. Some of the smaller features of the tomogram were not included in the model and may also be real. Common features between the real and model tomograms not related to the
Fig. 8 Pre-stack wavefield migration of the pressurized survey data looking down. Global scaling.

Fig. 9 Ray trace model and the model tomogram formed from the ray trace travel times. Refracting boundaries within the model are defined by the superimposed black lines and the zones of constant velocity are annotated in km s$^{-1}$.

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model are considered to be imaging distortions. Two such distortions can be identified, the band from lower left to top right and the high velocity around 450 m depth in the borehole on the right. Neither of these features is a particularly strong velocity anomaly but their prominence is accentuated by the colour contrast across the contour levels.

Apart from the two anomalous velocity features, the modelling has demonstrated that the remaining features can be interpreted as real. Although such an interpretation is not necessarily the only solution which fits the traveltime data it is supported by the borehole information and so is the preferred interpretation as it is consistent with all the available data.

**Reflector identification**

The migrated wavefield from the pressurized survey looking down is shown in Fig. 8. The lower part of the survey region is imaged best by the migration looking down because the number of source to diffraction point to receiver paths at each diffraction point increases in the direction in which the migration is looking and so the stacking is more effective in that direction. As the effectiveness of the stacking diminishes migration smiles become more prevalent.

Strong continuous events cutting the prevailing direction of migration smiles were interpreted as being reflections. For example, at the bottom left hand side of Fig. 8 there is a strong black horizontal alignment which stands out clearly above the noise and also a strong white over black alignment at 460 m depth just right of centre of the image.

**Difference tomograms and wavefield images**

To illustrate those reflections which were enhanced by the pressurization and suppress reflections common to the pressurized and unpressurized migrations, such as reflections due to lithological changes, the difference between the unpressurized and pressurized migrations was calculated (Fig. 10). This plot demonstrates that strong changes in reflectivity have been produced in the central and lower right portion of the migration region and at various locations along the boreholes. The strong events in the difference wavefield are interpreted as being due to the opening of fractures during the pressurization. In contrast, the strong event at the lower left in Fig. 10 has been attenuated in the difference image indicating that this event was a reflection from a lithological boundary, the top of the Gneiss at 477 m in FJB3, which was therefore present in both the pressurized and unpressurized wavefields.

The effects of the pressurization on the velocity field have been highlighted by subtracting the unpressurized from the pressurized tomogram to produce a difference tomogram (Fig. 11). The advantage of this approach is that, because the velocity distribution and ray coverage of the surveys were similar, imaging distortions tend to be removed by subtraction whereas the differences are enhanced. Reflectors interpreted from both the up and down views of the difference wavefield are shown as line segments superimposed on the difference tomogram for correlation.

In the difference tomogram areas of red correspond to an increase in velocity due to pressurization and areas of blue a decrease in velocity. The red anomaly in the top right of the

**Fig. 10** Difference wavefield looking down = pressurized wavefield - unpressurized wavefield. Global scaling.
Fig. 11 Difference tomogram = pressurized – unpressurized tomograms. The locations of reflectors interpreted from the difference wavefield, black lines, are superimposed.

The difference tomogram is not reliable due to a reduction in coverage of that region in the pressurized survey caused by four missing receiver gathers at the top of the survey region. In addition the relatively strong anomalies away from the boreholes at the very top and bottom of the tomogram are in the worst resolved parts of the tomograms and so may also be unreliable.

The changes in velocity detected were very small, typically less than 0.05 km s⁻¹ which is equivalent to 1% of the average velocity. There are distinct zones of reduced velocity in the lower portion of the right hand borehole which correlate with permeable zones in the borehole. These zones link up away from the borehole and extend towards the lower left hand corner of the tomogram. It is notable that there is no strong low velocity extending between the two boreholes, such as would be expected if there was a single distinct fracture zone linking the boreholes. There is also a less pronounced low velocity zone extending from around 470 m in the left hand borehole which correlates with a permeable zone and open fracture indicated by a strong tube wave.

The cause of the increased velocity zones is uncertain but may be due to compression of unconnected fractures compensating for the opening of fractures in permeable zones.

Conclusions
A crosshole field data set has been acquired using a downhole sparker source and string of hydrophone receivers both operating on standard seven conductor wirelines. Two surveys were performed across a fractured reservoir, one under ambient
borehole conditions and the second at an elevated downhole pressure. During each of these surveys in excess of 800 shots were fired with the sparker at a rate of one shot per 25 s. The acquisition of these data using standard wirelines and pressurediation equipment have demonstrated that the sparker and hydrophone borehole seismic system is compatible with conventional oilfield tool deployments.

The survey data have been processed using transmission tomographic velocity imaging and crosshole wavefield migration. An integrated approach to the interpretation of the reservoir region has been adopted utilizing the tomograms, forward modelling, wavefield images, difference images, tube data, lithologic logs and hydraulic data. In this way it has been possible to obtain a consistent interpretation of the distribution of fractures and stratigraphy in the interwell region on a scale of a few metres. In particular, the interpretation of the crosshole data suggest that there are comparatively few fractures linking the main permeable zone in the injection well to the more spatially extensive permeable zones in the recovery well. This interpretation is consistent with the results of hydraulic interference tests which found a high impedance between the wells.

**Acknowledgements**

This work was sponsored by the EC under the Thermie project DG/00125/94/UK/SE and by Notek of Sweden and CSMA who are gratefully acknowledged. We would also like to acknowledge Andy Jupe (CSMA) for his support in setting up the project, Paul Jacques (CSMA) for ensuring the tools were deployed and retrieved safely and to Thomas Eliasson (Swedish Geological Survey) and the staff and students of Chalmers University, Gothenburg for their assistance with the fieldwork.

**References**


*Received December 1996; received February 1997; accepted March 1997*