GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 20, PAGES 3169-3172, OCTOBER 15, 1999

PKP(BC-DF) travel time residuals and short scale heterogeneity in the deep earth

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Abstract.
Differential PKP(BC)-PKP(DF) travel time residuals for quasi-polar paths in the earth present large excursions from the trends predicted by simple models of inner core anisotropy. We analyze a set of such paths classified according to specific source and station regions, and show that observations are compatible with a constant anisotropy model of at most 1.5% in the outer 400 km of the inner core. To explain local departures of up to 3 sec from the predictions of such a model, strong lateral variations on scale lengths shorter than a few hundred km need to be invoked, either in the core or in the mantle. Independent results of D" modelling argue in favor of an important contribution from the latter.

Introduction

Proposed thirteen years ago [*Morelli et al.*, 1986; *Woodhouse et al.*, 1986], the anisotropy of the earth's inner core seems today firmly established, the fast axis of iron crystals being roughly aligned with the earth's axis of rotation. Yet, there is still no consensus as to what the exact distribution and strength of this anisotropy are. Some authors have favored constant anisotropy ranging from 1 to 3.5% [e.g. *Shearer and Toy*, 1991; *Creager*, 1992], while others have argued that the top 90-250 km of the inner core is isotropic [*Song and Helmberger*, 1998]. A recent study has shown that anisotropy is not evenly distributed with longitude, and that less than two thirds of the inner core might be anisotropic [*Tanaka and Hamaguchi*, 1997]. Normal mode studies call for a predominantly axisymmetric pattern of anisotropy, but alternative interpretations, for anomalous splitting have also been proposed [*Widmer et al.*, 1992; *Romanowicz and Bréger*, 1999].

Unfortunately, our knowledge of inner core structure relies mostly on waves which are sensitive to deep mantle heterogeneity, such as PKP(AB), PKP(BC), and PKP(DF) (Figure 1a) (hereafter called AB,BC, and DF). To reduce the contamination due to mislocation effects and mantle structure, differential travel times, such as BC-DF and AB-DF have been frequently used [e.g. *Shearer and Toy*, 1991; *Creager*, 1992; *Vinnik et al.*, 1994]. Strong lateral variations in the D" region have on the other hand been recently quantified [*Bréger and Romanowicz*, 1998; *Ritsema et al.*, 1998], with, in particular, patches with velocity reductions in excess of 10% over thicknesses of up to 50km and lateral extents of a few hundred km [ULVZ, e.g. *Garnero et al.*, 1998]. *Bréger et al.* [1999] showed recently that AB-DF differential travel times could largely be explained by deep mantle structure, including the trend with angle of the path with respect to the earth's rotation axis, usually attributed to inner core anisotropy. Because BC and DF propagate very close to each other in the mantle (Figure 1a), BC-DF travel times are in principle much less sensitive to mantle structure. Understanding and quantifying the effect of the mantle on BC-DF differential times is important since it will help to better resolve the fine structure of the inner core. In what follows, we present and discuss such effects based on a combination of hand-picked and bulletin PKP data.

Datasets

We have compiled the measurements of *Tanaka and Hamaguchi* [1997], *Souriau and Romanowicz* [1997], *Li and Richards* [1998], and *Wysession* (unpublished data), complemented by some of our own picks in order to obtain a representative dataset of 608 BC-DF differential travel time residuals. Residuals were computed with respect to reference model ak135 [*Kennett et al.*, 1995], and are plotted in Figure 1b-c as a function of the angle between the ray at its turning point and the earth's axis of rotation (hereafter called ξ), and as a function of the longitude of the event epicenter. Polar paths

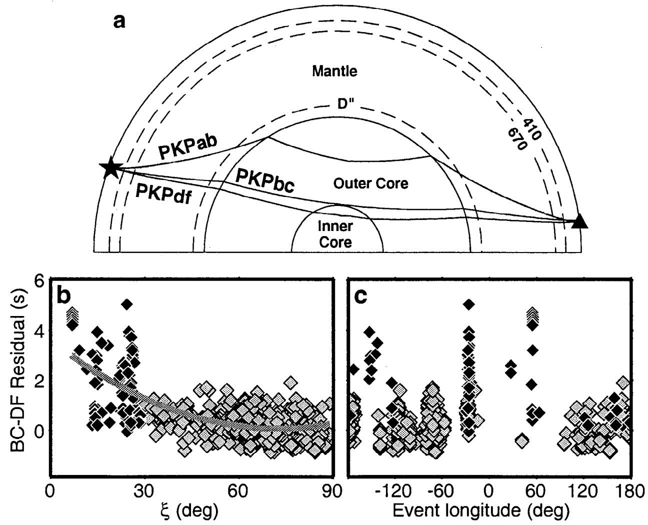

Figure 1. (a) Schematic representation of the wavepaths discussed in this study, and BC-DF differential travel time residuals plotted as a function of (b) angle between the ray at its turning point and the earth's spin axis, ξ , and (c) the longitude of the earthquake. Darker symbols correspond to quasi-polar paths ($\xi < 30^o$).

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Paper number 1999GL008374.
0094-8276/99/1999GL008374$05.00

lead to the largest values, but their distribution is very non uniform. A small number of points are responsible for creating the large scale trend with ξ. Most of these correspond to events in the South Sandwich Islands (longitude around -25^o on Figure 1c) but many other polar paths lead to small residuals. Although the average variations can be explained by cylindrical inner core anisotropy, data binned by angle ξ present highly variable values ranging from -1 to 4s, and cannot be explained by such a simple model (Figure 1b).

By fixing a station and comparing residuals in a given source region, it is possible to gain insight into small scale spatial variations. Station COL, in Alaska, is unfortunately the only one for which a relatively large dataset of hand-picked BC-DF travel times on quasi-polar paths is available, and the complexity of this dataset has been noted previously [*Creager*, 1997].

On the other hand, International Seismological Center (ISC) bulletins provide a large dataset spanning several decades, used extensively in previous studies [*Morelli et al.*, 1986; *Shearer*, 1991; *Su and Dziewonski*, 1995]. One drawback of this dataset is that it is very noisy. However, it has recently been improved by systematic elimination of misidentified phases and earthquake relocation [*Engdahl et al.*, 1998]. From this improved catalog, we have extracted BC and DF absolute travel time residuals with respect to the ak135 model [*Kennett et al.*, 1995] for a number of key stations corresponding to polar paths (Figure 2) and classified them by source region. For a given region, the scatter of the residuals gives a direct estimate of the data quality, and poor subsets can be rejected. A second drawback of the ISC dataset is that measurements of both BC and DF travel times for the same event/station pair are infrequent. However, when absolute residuals show systematic trends as a function of epicentral distance

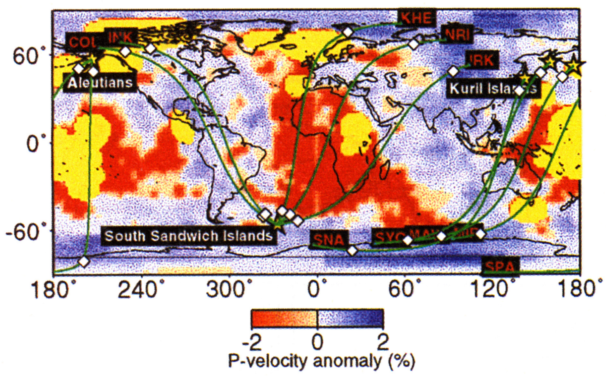

Figure 2. Near polar source-receiver paths analysed in this study. Stations, source regions, and great circle paths are indicated by blue triangles, yellow stars, and green lines respectively. Plotted as background is Grand et al.'s [1997] tomographic model for which we have converted S-velocity to P-velocity using the scaling dlnVs/dlnVp=2. This model was found to be a good starting point to describe the large scale distribution of P-velocity in D" on the global scale [*Bréger et al.*, 1999], including low velocity regions in the Pacific and under Africa. Yellow patches indicate the regions where Ultra Low Velocity Zones [*Garnero et al.*, 1998] have been detected. Outer core DF penetration points are indicated by white diamonds.

and angle ξ, it is possible to estimate the corresponding variations of BC-DF and their standard deviations in a "composite" fashion, as illustrated in Figure 3a for station COL. In this particular case, the comparison with hand-picked data shows good agreement (Figure 3a). In what follows, we present and discuss trends observed for a number of polar paths for which a sufficient number of ISC data are available to robustly estimate trends with epicentral distance Δ and angle ξ.

Results

The path between events in the S. Sandwich Islands and North America is well documented. BC-DF differential residuals have generally large values. At station COL in Alaska, composite BC-DF residuals range from about 3.5s for southermost events (Δ=154^o), to roughly 2s for northernmost events (Δ=149^o). Station INK is located 660km northeast of COL. Absolute DF and BC residuals from the ISC dataset also show systematic trends, and composite BC-DF residuals are in agreement with the few broadband data available (Figure 3b). They are 1 to 1.5s smaller than for station COL. The data at station COL are, on average, compatible with a model of 3.5% constant anisotropy in the inner core, but such a model overestimates the anomalies at INK (Figure 3b).

Similar systematic trends are obtained for S. Sandwich Island events observed at a group of stations in Eurasia (KHE, NRIL, IRK), yielding robust composite BC-DF residuals (Figure 3c). For these 3 neighboring stations, trends with angle ξ (and also Δ, not shown) are very different. At station KHE, there is practically no variation with ξ, whereas NRIL shows a strong increase with increasing ξ and latitude (ranging from 0 to 3 sec) opposite to what is expected from a simple model of inner core anisotropy. At station IRK, BC-DF residuals increase mildly with ξ and latitude. At all three stations, estimated residuals from an inner core model with constant 3.5% anisotropy largely overpredict the observations, whereas a 1.5% model underpredicts residuals at NRIL and still overpredicts those at KHE and IRK (Figure 3c), even though KHE corresponds to particularly small values of angle ξ, where the effect of inner core anisotropy should be most pronounced.

On the other hand, we note that paths to these three stations are such that, on the source side, entry points of BC and DF into the core plot at the southwestern edge of the large low velocity zone present in tomographic models in D" under Africa ("African Plume", Figure 2) where strong lateral gradients of structure have been proposed to explain observed variations of AB-DF residuals [*Bréger et al.*, 1999]. Thus a significant contribution of D" heterogeneity to the observed anomalies along these paths is likely.

The trends observed for high latitude earthquakes recorded at Antarctica stations SNA, MIR, SYO MAW, and SPA show a wide range of behaviours. Relatively small and stable BC-DF residuals are recorded at SYO and SNA, between -0.5 and 0.5 sec. Neighboring stations MIR and MAW, on the contrary, lead to residuals that vary with the position of the earthquake. Although the two stations correspond to similar paths (Figure 2), lateral variations of 2.5s sec are implied on a scale of just a few degrees in Δ. ISC data for events in the Aleutians recorded at SPA suggest, on the other hand,

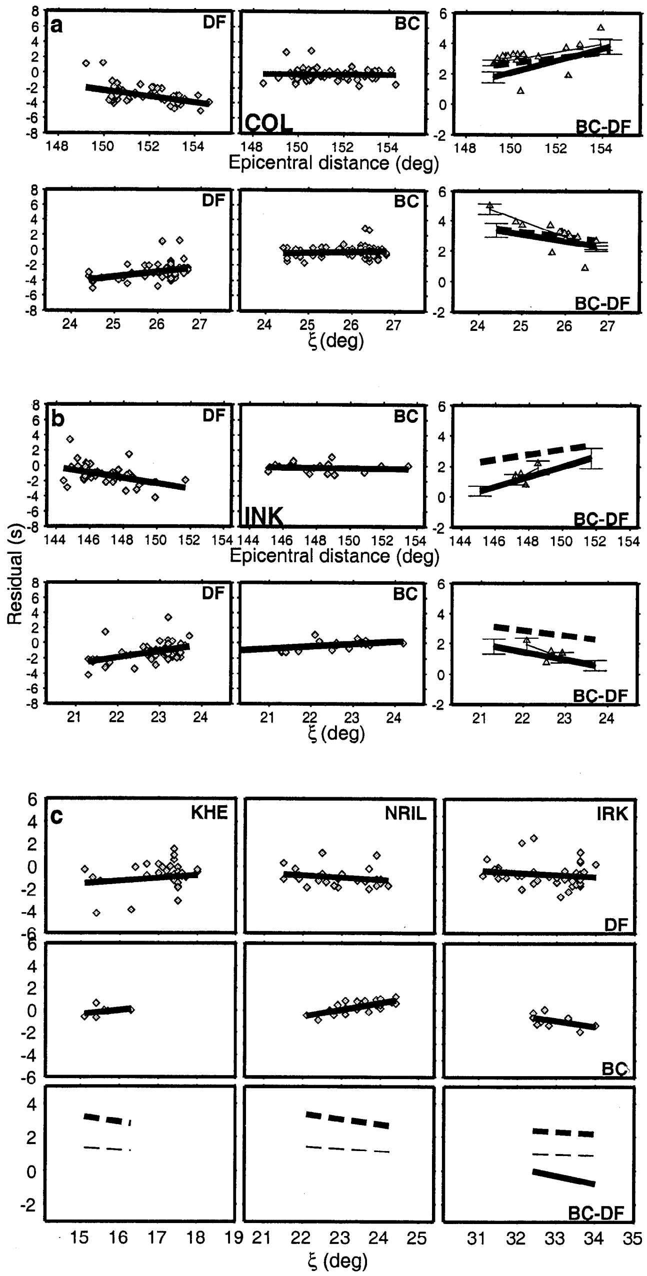

Figure 3. (a) Reprocessed ISC residuals (diamonds) for station COL. Composite BC-DF variations (thick continuous lines) were obtained by substracting the linear regression obtained for DF from that obtained for BC. Also plotted are the predicted variations for Creager's [1992] 3.5% inner core anisotropy model (thick dashed line), and observed hand picked residuals (triangles and thin line). (b) Same as Figure 3a for station INK. (c) Observed ISC residuals (diamonds and thick continuous lines) for KHE, NRIL and IRK respectively, as well as predictions for Creager's [1992] 3.5% inner core anisotropy model (thick dashed lines), and a 1.5% inner core anisotropy model (thin dashed line). Regression lines have been added to outline the trends in the residuals. In order to obtain the trends predicted by simple models of inner core anisotropy, we computed synthetic residuals corresponding to the DF observations, and determined the best fitting linear trend through those residuals. Some of the positive outliers in the DF residuals may be due to misidentified BC phases corresponding to a peak at 1.5 sec in the ISC bulletin residual data. However, removing these outliers does not significantly change the regressions obtained.

some strong lateral variability, with BC-DF residuals changing rapidly from 0.5 to 3s.

Discussion

In order to summarize the observed trends for quasi-polar paths, we have plotted the composite BC-DF travel time anomalies as a function of angle ξ (Figure 4) for all 10 stations discussed above, compared to predictions from different simple models of inner core anisotropy. Figure 4 shows large excursions, both locally and over the range of ξ considered, from a trend that is compatible with the predictions of a model of anisotropy with strength on the order of 1.5%, at least for the top 400km of the inner core.

In order to explain our observations, a very complex model of inner core anisotropy, possibly associated with heterogeneity, needs to be invoked. The inner core structure would change on a hemispherical scale [*Tanaka and Hamaguchi*, 1997], but also over distances of a few hundreds of kilometers, from one station to another, and on even shorter scales, when the station is fixed (Figure 4). Some very large residuals are sometimes observed: hand-picked residuals at station COL vary from 2s to exceptionnal values of some 5s. An anisotropy of more than 5% would be required in order to speed up DF by 5s at 154^o. This is extremely high since the intrinsic anisotropy of hcp iron at inner core pressures is expected to be around 3 to 4% [*Stixrude and Cohen*, 1995], but could be compatible with the results of recent high-pressure experiments [*Mao et al.*, 1998] and the existence of a complex convective pattern [*Jeanloz and Wenk*, 1988].

A complex lowermost mantle structure could be an alternative explanation to this complex behaviour. BC-DF travel times are not anomalous for polar paths for roughly one third of the globe, over Asia and Russia [*Tanaka and Hamaguchi*, 1997]. Interestingly, the deep mantle beneath these regions seems weakly anomalous: they exclude the two large African and Pacific plumes, tomographic models predict comparatively very little heterogeneity, no ULVZs have so far been detected [*Garnero et al.*, 1998], there are no hotspots at the surface, and little fossil lithosphere is expected at the

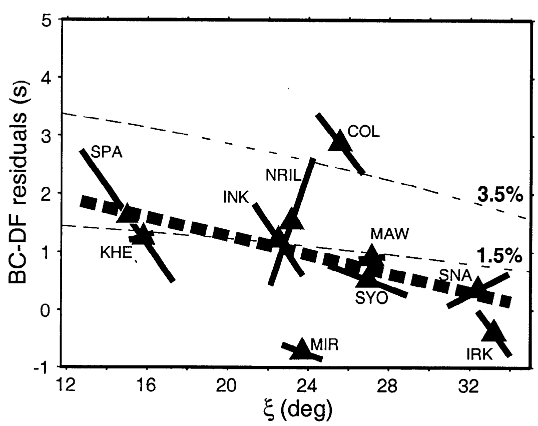

Figure 4. Summary of the estimated variations of BC-DF travel time residuals for polar paths. Triangles represent the mean values of the extrapolated residuals, and the thick black lines their variations as a function of ξ. The thick dashed line represents the average observed linear trend, and is compared with the predictions for 3.5% and 1.5% anisotropy (thin dashed lines) at 148^o epicentral distance.

CMB [*Lithgow-Bertelloni and Richards*, 1998]. On the other hand, some of the largest residuals are obtained at station NRIL (Figure 3c), for which there could be a strong interaction of the PKP paths with the base of the African plume(Figure 2).

DF and BC are separated at the CMB by a few hundred kilometers, and have Fresnel zones of about the same size. A combination of small scale lateral variations in D" with contrasts on the order of 4%, ultralow velocity zones, and additional heterogeneity in the deep mantle above D", could add up to differential residuals in excess of 3s for exceptional geometries in which both source and station legs are affected. Indeed, for quasi equatorial geometries, some residuals exceeding 3s are also observed. Explaining the very exceptional and rare observations of up to 5 sec at station COL remains nevertheless a challenge for this lower mantle interpretation, although it is important to note that this unusually large residual could be reduced to about 3.9s if it was computed with respect to PREM reference model [*Dziewonski and Anderson*, 1981].

Although BC and DF propagate very close to one another in the upper mantle, and although we analyse the variations of BC-DF residuals for paths with almost the same azimuth, upper mantle extreme structures, such as slabs, might also affect BC-DF residuals [*Hellfrich and Sacks*, 1994]. At present, is not possible to separate this effect from that of D".

The rapid variations of BC-DF residuals on scales of a few hundreds kilometers can be understood as an effect of very complex anisotropic structure at the top of the inner core, or mantle heterogeneity, or a combination of both. Lowermost mantle structure happens to geographically correlate with the complex behaviour of BC-DF residuals, in locations where it is well documented. Whatever their origin, the existence of such strong variations shed a new light on the complexity of the deep earth.

Acknowledgments. We are particularly grateful to A. Souriau and G. Poupinet, M. Wysession, P. Richards, and S. Tanaka and H. Hamaguchi for providing us with their data, and E. R. Engdahl, R. van der Hilst, and R. Buland for making their ISC dataset available. We benefited from discussions with H.R. Wenk and R. Jeanloz. We also thank the IRIS, CNSN, Geoscope, GRSN, Mednet, BDSN, SCSN, and GRSN teams. Figures were made with the G. M. T. (P. Wessel and W. H. F. Smith, *EOS Trans. AGU* **76**, 329, (1995)). This work was partially supported by IGPP/LLNL grant #99-GS013. It is BSL contribution 99-05.

References

Bréger, L., and B. Romanowicz, Three-Dimensional structure at the base of the mantle beneath the Central Pacific. *Science*, *382*, 718-720, 1998.

Bréger, L., H. Tkalcic, and B. Romanowicz, The effect of D" on PKP(AB-DF) travel time residuals and possible implications for inner core structure, Submitted to *Earth Planet. Sci. Lett.*, 1999.

Creager, K.C., Anisotropy of the inner core from differential travel times of the phases PKP and PKIKP, *Nature*, *356*, 309-314, 1992.

Creager, K.C., Inner core rotation rate from small-scale heterogeneity and time-varying travel times, *Science*, *278*, 1284-1288, 1997.

Dziewonski, A. M., and D.L. Anderson, Preliminary Reference Earth Model. *Phys. Earth Planet. Int.*, *25*, 297-356, 1981.

Engdahl, E.R., R. van der Hilst, and R. Buland, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. Seismol. Soc. Am.*, *88*, 722-743, 1998.

Garnero, E.J., J. Revenaugh, Q. Williams, T. Lay, and L.H. Kellogg, *The Core-Mantle boundary*, Ed. Gurnis, M., Buffett, B.A., Knittle, E. and M. E. Wysession, 319-334, American Geophysical Union, Washington, DC, 1998.

Grand, S., R. van der Hilst, and S. Widiyantoro, Global seismic tomography: a snapshot of convection in the Earth, *G.S.A. Today*, *7*, 1-7, 1997.

Hellfrich, G., and S. Sacks, Scatter and bias in differential PKP travel times and implications for mantle and core phenomena, *Geophys. Res. Lett.*, *21*, 2167-2170, 1994.

Kennett, B.L.N., E.R. Engdahl, and R. Buland, Constraints on seismic velocities in the Earth from travel times, *Geophys. J. Int.*, *122*, 108-124, 1995.

Jeanloz, R. and H.R. Wenk, Convection and anisotropy of the inner core, *Geophys. Res. Lett.*, *15*, 72-75, 1988.

Li, A., and P.G. Richards, Study of inner core travel times using nuclear explosion data. *Eos (Spring Suppl.)*, *75*, 232, 1998.

Lithgow-Bertelloni, C., and M.A. Richards, The dynamics of Cenozoic and Mesozoic plate motions, *Rev. Geophys.*, *36*, 27-78, 1998.

Mao H., J. Shu, G. Shen, R.J. Hemley, B. Li, and A.K. Singh, Elasticity and rheology of iron above 220 GPa and the nature of the Earth's inner core, *Nature*, *396*, 741-743, 1998.

Morelli, A., A.M. Dziewonski, and J.H. Woodhouse, Anisotropy of the core inferred from PKIKP travel times, *Geophys. Res. Lett.*, *13*, 1545-1548, 1986.

Ritsema, J., S. Ni, D.V. Helmberger, and H.P. Crotwell, Evidence for strong shear velocity reductions and velocity gradients in the lower mantle beneath Africa, *Geophys. Res. Lett.*, *25*, 4245-4247, 1998.

Romanowicz, B., and L. Bréger, Anomalous splitting of free oscillations : a re-evaluation of possible interpretations, Submitted to *J. Geophys. Res.*, 1999.

Shearer, P.M., and K.M. Toy, PKP(BC) versus PKP(DF) differential travel times and aspherical structure in the Earth's inner core, *J. Geophys. Res.*, *96*, 2233-2247, 1991.

Song, X.-D., and D.V. Helmberger, Seismic evidence for an inner core transition zone. *Science*, *282*, 924-927, 1998.

Souriau, A., and B. Romanowicz, Anisotropy in the inner core; relation between P-velocity and attenuation, *Phys. Earth Planet. Inter.*, *101*, 33-47, 1997.

Stixrude, L., and R. Cohen, R. High-pressure elasticity of iron and anisotropy of Earth's inner core, *Science*, *275*, 1972-1975, 1995.

Su, W., and A.M. Dziewonski, Inner core anisotropy in three dimensions, *J. Geophys. Res.*, *100*, 9831-9852, 1995.

Tanaka, S., and H. Hamaguchi, Degree one heterogeneity and hemispherical variation of anisotropy in the inner core from PKP(BC)-PKP(DF) times, *J. Geophys. Res.*, *102*, 2925-2938, 1997.

Vinnik, L., B. Romanowicz, and L. Bréger, Anisotropy in the central part of the inner core, *Geophys. Res. Lett.*, *21*, 1671-1674, 1994.

Widmer, R., G. Masters, and F. Gilbert, Observably split multiplets-data analysis and interpretation in terms of large-scale aspherical structure, *Geophys. J. Int.*, *111*, 559-576, 1992.

Woodhouse, J.H., D. Giardini, and X.-D. Li, Evidence for inner core anisotropy from splitting in free oscillation data, *Geophys. Res. Lett.*, *13*, 1549-1552, 1986.

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(received June 8, 1999; revised June 29, 1999; accepted July 8, 1999.)