行政院國家科學委員會專題研究計畫　成果報告

全球 P 波波速三維構造之多重尺度層析成像(2/2)

計畫類別：個別型計畫
計畫編號：NSC92-2611-M-002-021-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：國立臺灣大學海洋研究所

計畫主持人：喬凌雲
共同主持人：洪淑蕙

報告類型：完整報告

處理方式：本計畫可公開查詢

中　華　民　國 93 年 12 月 13 日

行政院國家科學委員會專題研究計劃成果報告

全球 P 波波速三維構造之多重尺度層析成像(2/2)
Mantle heterogeneity of P-velocity by multiscale seismic tomography

計畫編號：NSC 91-2611-M-002-021
執行期限：92 年 8 月 1 日至 93 年 7 月 31 日
主持人：喬凌雲　　執行機構及單位名稱：台灣大學海洋研究所

一、中文摘要

利用短週期走時資料進行層析成像以建構全球 P 波波速三維構造模型開始迄今十九年以來，對於提供地球深層重要的構造線索，以至於系統化的改變地球物理學者對於地表觀測與深部動力機制聯繫的瞭解已有深遠之影響。初步的圖像顯示各種尺度的作用在熱鬧紛擾的上地幔中直接與扮演熱邊界層的岩圈互動；而尺度偏“紅”，即只有相對大尺度，以古隱沒岩圈與地幔熱柱組成低球階(L_2)為主的下地幔究係核幔邊界之影射或特殊走時取樣建構之取景窗制所模塑則引起重要的地球研究新領域。層析成像當然不是提供地球深處訊息的唯一途徑，但是此一研究方法確實仍有進步空間。過去十數年間，逆推方法日趨成熟，數值計算資源與方法亦突飛猛進，更重要的則是資料品質大幅改善與數量顯著累積。但是各研究群所發表之結果仍有顯著之崎異與爭議。其原因固可訴諸各自之參數化、正則化以及計算等方法之異同以及所採用資料組合的差別。對於 P 波走時資料而言，我們與 USGS 之 Dr. Engdahl 聯繫,取得其結合 ISC 與 NEIC 並且重新定位所編纂之走時資料。該筆資料提供了目前為止， 短週期 P 波走時資料品質最統一而數量最為豐富之資料組合。本研究已先後完成的工作包括發展新的全球線性小波基底,大幅改善原來的不連續問題(其中並且成功推導完成高階趨近之三維數值積分的高斯取樣位置以及權重)；利用觀測走時資料建構三維經驗走時分佈 (empirical traveltimes)並據以組織代表射線(summary rays)以便在不影響實際資訊含量前提下大幅壓縮資料量並改善取樣之幾何。初步完成之 1998-2001 部分資料的全球 P 波波速層析成像顯示與其他研究團隊相似的結果，即上上地慢(約在深度 400 公里以上)之構造與大地塊體構造包括洋脊、隱沒岩圈等分佈有極佳的耦合，下地慢則以前述之 L_2 型態為主。由於整體資料量過於龐大，雖經代表射線處理仍無法同時逆推所有資料以盡量發揮多重尺度逆推對解析能力之改善、如何突破此一困境將是爾後努力的方向，

關鍵詞：全球 P 波波速三維構造, 全球遠距震央重新定位, 經驗走時變化, 多重尺度層析成像。

二、英文摘要：

It has already been 19 years since the first global seismic traveltime tomography using the short period teleseismic P-arrivals. Significant contributions made upon improving our knowledge of the deep interior of the Earth have been made. In recent years, due to the fast accumulation of traveltime data of improved quality, the continuously growing computing-power and the development of inversion techniques, more and more global models of P velocity heterogeneity, each with their own nominal resolution, have been reported from different research groups. However, there are still significant controversies among these published models in terms of highlighting the structure of the deep interior of the Earth. These ambiguities might be attributed to either different adopted data sets or different schemes of parameterization, regularization and inversion algorithms. We have established communication with Dr. Engdahl of the United States Geological Survey (USGS), and obtain and compiled the updated travel time data since Engdahl et al. (1998). They have relocated hundred-thousands of events that are well-constrained teleseismically by arrival-time data reported to the International Seismological Centre (ISC) and to the U.S. Geological Survey's National Earthquake Information Center (NEIC). We believe that by adopting the same data set, it is a good opportunity to clearly appraise the implications of the inverted P-velocity model obtained from different inversion techniques. Up to now, we have succeeded, within this research, developing the first fully 3-D, linear spherical wavelet bases that significantly improves upon the discontinuity problem embedded within the original spherical Haar basis developed by our previous work (along with the derivation of the 3D Gaussian sampling and weighting functions needed for the high order approximation of the numerical integration that builds the Gram matrix); as well as building the Empirical TravelTimes (ETT) directly from the observed traveltime data and constitute a better set of summary rays that both reduces the total amount of observations and improves the sampling geometry without sacrificing useful information embedded within the raw data.

Preliminary inversion performed upon the subset built from the 1998-2001 data has revealed results similar to tomographic models built by other leading groups. That is, we have very good correlation between the P-velocity structure and the dynamics implied from the surface tectonics such as the distribution of ridges and subducted slabs within the top of upper mantle (above about 400 km depth); and the pronounced large-scale L_2, lowermost mantle structure. It is unfortunate that our current setup cannot handle such humongous size of the Engdahl data set (over millions of rays for just the 1998-2001 subset) even after we have cleverly go through the summary ray processing by the previously mention, new EET scheme. To overcome this difficulty is certainly the most important focus of our future work such that the multiscale tomography that has been developed by our group that is the only inversion scheme naturally equipped with a non-stationary regularization scheme and may potentially pushes the resolution to the upper limit of what the data constraints might impose. We will continue our research in this respect.

Keywords ： Mantle P-heterogeneity, Global teleseismic earthquake relocation, Empirical traveltimes, Multiscale seismic tomography.

三、研究計畫之背景及目的

Detailed 3-D configuration of complicated plate interaction near Taiwan inferred from tomography model of global P-velocity heterogeneity (Lallemand et al., 2001) has caused noticeable stir in the local geoscientist community. The original tomography work (Bijwaard et al., 1998) is one typical example of recent global body wave tomography. Earlier works of global body wave tomography dated back to almost 20 years ago (Clayton and Comer, 1983; Dziewonski, 1984) and have significantly shaped some important research fields in the past two decades. Subsequently, short-period, vertical-component first-arrivals of P compiled by ISC that amounts easily into several million, have been used in the tomographic studies of 3-D structure (Creager and Jordan, 1986; Morelli et al., 1986; Morelli and Dziewonski, 1987; Shearer et al., 1988; Inoue et al., 1990; Pulliam et al., 1993; Vasco et al., 1993; Vasco and Johnson, 1998; Su and Dizewonski, 1997; Vander Hilst et al., 1997; Zhou, 1996; Kennett et al., 1998; Bijwarrd et al., 1998; Masters et al., 2000). A major reprocessing of the ISC data set has been undertaken by Engdahl et al. (1998, hereafter EHB) with particular attention paid to the problem of misidentification of depth phases for direct phases (Masters et al., 2000). The most recent tomographic modeling taking advantages of this reprocessed data set include Van der Hilst et al. (1997), Bijwaard et al. (1998), Kenett et al. (1998) and Masters et al. (2000).

Despite of all the progression of the tomography works and the higher and higher nominal resolutions reported from different groups (e.g., Grand et al., 1997), there are still fundamental controversies concerning the obtained pattern of velocity heterogeneity within the mantle (e.g., Stark, 1995; Megnin et al., 1997; Boschi and Dziewonski, 1999; Chiao and Kuo, 2001). Due to the immense size of global data and the model degrees of freedom, formal appraisal of the resolution and the robustness of the obtained model are usually hard to come by. Theoretical derivation of potential bias from improper parameterization and *ad hoc* regularization have been reported (e.g., Trampert and Snieder, 1996; Chiao and Kuo, 2001) but have not been applied to evaluating the global P-velocity heterogeneity models. Of such derivations, we have previously derived the generic relationship between the commonly adopted truncated-expansion approach and the actual continuous tomography (Chiao and Kuo, 2001). One experience we obtained from our previous works is that invoking multiscale parameterization not only resolves the problem that non-stationary sampling demands non-stationary regularization, it also yields more robust inversion result. We intend to thus extend the previously 2D spherical wavelet representation into a fully 3D global parameterization scheme with possibly higher order of vanishing moments. One important goal is aimed at revealing the intrinsic dependence of the formerly obtained structure patterns on the local sampling. For example, how much are the apparent slab features from upper- to mid- and then lower-mantle affected by the imposed smoothness correlation and the local sampling density? This information would be critical not only for examining the interpreted global, dynamic structure, but also for accessing local plate configurations and tectonic implications such as the one reported for the Taiwan area by Lallemand et al. (2001).

The adjoint operator for wavelet representation of the velocity model

Previously, we have stressed the importance of building biorthogonal wavelets to achieve the multiresolution analysis of global tomography. The rationale is simply that biorthogonality enables us to very easily transform a pixel-based formulation of a global tomographic problem into the desired multiresolution representation (Chiao and Kuo, 2001). Formally, we can now take advantage of the notation of the adjoint operator of the inner product defining the continuous data rule,

$$d_i = (g_i, m) = (W^{-1}Wm, g_i)\,, \tag{1}$$

where m is the pursued continuous function representing the velocity heterogeneity, *Wm* stands for the multiresolution representation of the model function (the wavelet transform of *m*), W^{-1} is the inverse wavelet transform (synthesizing from *Wm*). If we define the adjoint operator, W^*, as the wavelet transform of the data kernel, $W^* g_i$, using the dual wavelet basis functions biorthogonal to the primary wavelet bases used for *Wm*, then equation (1) can be rewritten as

$$d_i = (g_i, m) = (Wm, W^* g_i)\,, \tag{2}$$

due to the biorthogonality between the primary and the dual bases invoked in *W* and W^*. The new syntax is now written in terms of the continuous data rule. Expression (2) turns out to be a general and more natural way of devising regularization as well as for making comparisons among different tomographic models. It also shed lights on the origin of the classical variance – resolution tradeoff (Chiao and Lin, unpublished manuscript) that has been the corner stone of the modern inverse theory. Furthermore, when it is applied in the multiscale inversion, where the wavelet transforms take advantage of the merit that due to the usually fast decaying rate of the wavelet coefficients across scales (at least O($2^{-(j+1)}$), *j* being the invoked scale level), it might potentially justify the inevitable truncation and may be a convenient way of avoiding the spectral leakage problem (Trampert and Snieder, 1996; Chiao and Kuo, 2001).

Spherical wavelets: bio-Haar and vertex-based wavelets with more vanishing moments

Although merits of our previously discussed multiscale seismic tomography has been clearly demonstrated (Chiao and Kuo, 2001; Chiao and Liang, 2003), establishing the multiresolution analysis (MRA) on the non-Euclidean spherical surface has not been easy. We followed Schroder and Sweldens (1995) and constructed the bio-Haar basis that was probably the first formulation applied to spherical tomography. The construction was built from the spherical icosahedron and went through hierarchical subdivision across 5 scale levels. However, the bio-Haar wavelet bears only one vanishing moment and suffers from the lack of smoothness and visual continuity. We have developed successfully, in this study, the linear and quadratic vertex-based formulation that appear more continuous visually. Additional orders of vanishing moment have been achieved by invoking the *lifting* scheme (Sweldens, 1996). These formulations of course preserve the most critical quality of imposing non-stationary correlation regularization depending on the non-stationary sampling. That is, they are still being *data-adaptive*.

四、結果與討論

We have established communication with Dr. Engdahl of the United States Geological Survey (USGS), and obtain and compiled the updated travel time data since Engdahl et al. (1998). They have been relocating hundred-thousands of events that are well-constrained teleseismically by arrival-time data reported to the International Seismological Centre (ISC) and to the U.S. Geological Survey’s National Earthquake Information Center (NEIC). Up to now, this is the most abundant data set that is of uniform quality. We’ve built up codes that efficiently trace rays through the Earth for most of the major phases collected within this particular data set, and thus established the travel time residuals that constrain our pursued perturbation of the P velocity. We have also constructed summary rays based upon our particular surface parameterization and a new technique that constructs the empirical traveltimes (ETT, Nicholson et al., 2004) first that yield robust and reliable data constraints. The ETT construction significantly reduces the total amount of the raw data and improves the data quality (Fig.1) by summarizing redundant rays that impose unfair weighting on certain frequently observed rays. The advantage can be shown by an example examining the traveltimes observed by the station WRA before (left of Figure 1) and after (right of Figure 1) the EET building is affective.

We had proposed to further develop our previously derived multiscale tomography scheme into a fully global 3-D method to examine the particularly important issues such as the influences on the resolution and robustness from parameterization, regularization of a highly non-stationarily sampled inverse problem. Up to now, we’ve successfully developed new, 3D, linear wavelet bases that greatly improves the discontinuous characteristics that we developed previously. Furthermore, the locations and weights of the 3D Gauss integration points for numerical integration bearing high order approximation to the volume integration involved with the data rule has been carefully derived (see Appendix of the midterm report). Cleverly constructed summary rays helps to improve the data quality significantly. However, the data set is still too sizeable such that we have not been able to take the full advantage of the data set and pursue the highest achievable resolution.

五、計劃成果評估

The proposed research has been progressing smoothly. But the P.I. has failed to foresee the obstacles of the paging and memory limits of modern compilers on PCs which has prevented us from going in full speed into inverting and constructing the global P velocity model under the efficient regularization of our multiresolution parameterization. Preliminary experiments on smaller subset have been very successful. The next goal of this study is certainly to overcome this difficulty by considering more serious workstations or change the strategy to examining regional, well known, controversial structures first to further reduces the data set. With the gained experiences, resources and newly developed concepts and techniques we are more than comfortable in pursuing leadership in both global and regional tomographic studies, and exploring both academic and industrial applications.

六、參考資料：

Bijwaard, H., Spakman, W., and Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography, *J. Geophys. Res.*, **103**, 30055-30078.

Boschi, L., and Dziewonski, A.M., 1999. High- and low-resolution images of the Earth’s mantle: Implications of different approaches to tomographic modeling, *J. Geophys. Res.* ,**104**, 25567-25594.

Chiao, L.Y., and Kuo, B.Y., 2001. Multiscale seismic tomography, *Geophys. J. inter.*, **145**, 17-527.

Chiao, L.Y., and Liang, W.T., 2001. Multiresolution parameterization for geophysical inverse problems, *Geophysics.*, **68**, 111-121.

Clayton, R.W., and Comer, R.P., 1983. A tomographic analysis of mantle heterogeneity from body wave travel time data, *EOS Trans. AGU*, 64, 776.

Creager, K.C., and Jordan, T.H., 1986. Large scale structure of the outermost core from P'_{DF} and P'_{AB} traveltimes, *EOS Trans. AGU*, **67**, 311.

Dziewonski, A.M., 1984. Mapping the lower mantle: Determination of lateral heterogeneity in P velocity up to degree and order 6, *J. Geophys. Res.*, 89, 5929-5952.

Dziewonski A.M., and Woodhouse, A.H., 1987. Global images of the Earth’s interior, *Science*, **236**, 37-48.

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

Grand, S.P., van der Hilst, R.D., and Widiyantoro, S., 1997. High resolution global tomography: a snapshot of convection in the Earth, *Geol. Soc. Am. Today*, **7**, 1-7.

Inoue, H., Fukao, Y., Tanabe, K., and Ogata, Y., 1990. Whole mantle P-wave travel time tomography, *Phys. Earth Planet. Inter.*, **59**, 294-328.

Kennett, B.L.N., Widiyantoro, S., and Van der Hilst, R.D., 1998. Joint seismic tomography for bulk sound and shear wave speed in the Earth’s matle, *J. Geophys. Res.*, **103**, 12469-12493.

Lallemand, S., Font, Y., Bijwaard, H., and Kao, H., 2001. New insights on 3-D plates interaction near Taiwan from tomography and tectonic implications, *Tectonophysics*, **335**, 229-253.

Mallat, S.G., 1989. A theory of multiresolution signal decomposition: the wavelet representation, *IEEE trans. pattern analysis and machine intelligence*, **11**, 674-693.

Masters, G., Laske G., Bolton, H., and Dizewonski, A., 2000. The Relative Behavior of Shear Velocity, Bulk Sound Speed, and Compressional Velocity in the Mantle: Implications for Chemical and Thermal Structure, in *Earth's Deep Interior: Mineral Physics and Tomography From the Atomic to the Global Scale* edited by Karato, S.-I., Forte, A.M., Liebermann, R.C., Masters, G., Stixrude, L., *Geophysical Monograph Series*, **117**, 289 pp.

Megnin, C., Bunge, H.-P., Romanowicz, B., and Richards, M.A., 1997. Imaging 3-D spherical convection models: What can seismic tomography tell us about mantle dynamics? *Geophys. Res. Lett.*, **24**, 1299-1302.

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

Morelli, A., and Dziewonski, A.M., 1987. The harmonic expansion approach to the retrieval of deep Earth structure, in: *Seismic Tomography*, ed. G. Nolet, Reidel.

Nicholson T., Sambridge, M., and Gudmundsson, O., 2004. Three-dimensional empirical traveltimes: constrruction and applications, *Geophy. J. int.*, **156**, 307-328.

Paige, C.C., and Saunders, M.A., 1982. LSQR: an algorithm for sparse linear equations and sparse least squares, *Trans. Mart. Software*, 8, 43-71.

Pavis, G.L., and Booker, J.R., 1980. The mixed discrete-continuous inverse problem: Application to the simultaneous determination of earthquake hypocenters and velocity structure, *J. Geophys. Res.*, **85**, 4801-4810.

Pulliam, R.J., Vasco, D.W., Johnson, L.R., 1993. Tomographic inversions for mantle P wave velocity structure based on the minimization of l^2 and l^1 norms of International Seismological Centre travel time residuals, *J. Geophys. Res.*, **98**, 699-734.

Schroder, P., and Sweldens, W., 1995. Spherical Wavelets: Efficiently representing functions on the sphere, *SIGGRAPH: Computer Graphics Proceedings, Annual Conference Series*, 161-172.

Shearer, P.M., Toy, K.M., and Orcutt, J.A., 1988.

Axi-symmetric earth models and inner core anisotropy, *Nature*, **333**, 228-232.

Su, W.-J., and Dizewonski, A.M., 1997. Simultaneous inversion for 3D variations in shear and bulk velocity in the mantle, *Phys. Earth Planet. Int.*, **100**, 135-156.

Sweldens, W., 1996, The lifting scheme: Accustom-design construction of biorthogonal wavelets, *Appl. Comput. Harmon. Anal.*, **3**, 186-200.

Thurber, C. H., 1993. Local earthquake tomography: Velocity and Vp/Vstheory, in *Seismic Tomography: Theory and Practice*, edited by Iyer, H.M. and K. Hirahara, 563-583.

Trampert J., and Snieder, R., 1996. Model estimations biased by truncated expansions: possible artifacts in seismic tomography, *Science*, **271**, 1257-1260.

Van der Hilst, R.D., Widiyantoro, S., and Engdahl, E.R., 1997. Evidence for deep mantle circulation from global tomography, *Nature*, **386**, 578-584.

Vasco, D.W., Pulliam, R.J., and Johnson, L.R., 1993. Formal inversion of ISC arrival times for mantle P-velocity structure, *Geophys. J. int.*, **113**, 586-606.

Vasco, D.W., and Johnson, L.R., 1998. Whole Earth structure estimated from seismic arrival times, *J. Geophys. Res.*, **103**, 2633-2671.

Zhou, H.-W., 1996. A high-resolution *P* wave model for the top 1200km of the mantle, *J. Geophys. Res.*, **101**, 27791-27810.

Figure 1