Published in *Natl. Acad. Sci. Lett. (2013) 36, 645-652*

Form and Function of Proteins. Historical Background and the Indian Effort in Macromolecular Crystallography

M. Vijayan

Introduction

Molecular structural biology is concerned with the structure of biomolecules, particularly biological macromolecules, and the relation of structure to function. In living organisms, genetic information is stored in DNA. Much of this information is on the amino acid sequences of different proteins. Once proteins are expressed using the information coded in DNA, much of the subsequent functions in life processes are performed by them. Proteins are truly multi-purpose molecules. They contribute to the structural integrity of living organisms and perform a central role in physiological processes. Although all proteins are built on the same principles, they exhibit bewildering structural and functional diversity. Therefore, structural biology is primarily concerned with the structure, assembly, interactions and function of proteins. The method of choice for structural studies of proteins is X-ray crystallography, although NMR has emerged, to a limited extent, as an alternative structural tool in recent decades. Much of what we know about the three-dimensional structure of proteins and structure-function relationship in them, has resulted from macromolecular crystallographic studies.

Some early history

The origin of macromolecular crystallography can be traced to the recording of the X-ray diffraction pattern from the crystals of pepsin by J.D. Bernal and his then graduate student Dorothy Crowfoot (subsequently Hodgkin) [1] who joined the Cavendish laboratory at Cambridge

Based on the Professor Krishnaji Award Lecture delivered by Prof. M. Vijayan on 28 February, 2013 at Allahabad

Molecular Biophysics Unit, Indian Institute of Science, Bangalore – 560012, e-mail: mv@mbu.iisc.ernet.in

for her doctoral programme after graduating from the University of Oxford. Dorothy returned to Oxford and recorded and studied the X-ray diffraction pattern from the crystals of insulin in 1935, as her first independent project [2]. Max Perutz, an Austrian refugee, working in Bernal's laboratory, crystallized hemoglobin and carried out preliminary crystallographic studies on the crystals of hemoglobin in 1937 [3]. Preliminary X-ray studies on a couple of other protein crystals were also carried out during this period. It was an act of faith on the part of pioneers like Bernal, Hodgkin and Perutz to have embarked on structural studies on proteins. Even the chemical nature of proteins was not then wholly established. The complete determination of protein structures must have appeared a distant dream. Yet the pioneers persevered.

In the meantime, fibre diffraction and modeling, individually or together, were making rapid strides. The fibre diffraction work of W.T. Astbury on fibrous proteins is well known. In a major advance, Linus Pauling and his colleagues discovered α-helices and β-sheets through simple modeling in the early fifties [4,5]. The proposal of the double helical model of DNA, made by Jim Watson and Francis Crick in 1953, marked the crowning glory of molecular modeling combined with fibre diffraction data [6]. The elucidation of the triple helical coiled-coil structure of collagen by G.N. Ramachandran and Gopinath Kartha in 1955 was yet another land mark in the development of structural biology during that period (Figure 1) [7].

The Gobal Scenario

Definitive results on the structure of globular proteins began to emerge only around 1960. The first protein structures to be solved were those of myoglobin and hemoglobin by the groups of John Kendrew and Max Perutz respectively [8,9]. The structure of lysozyme, the first enzyme to be X-ray analysed, was determined by David Phillips and his colleagues in 1964 [10]. This work also provided the first image of an enzyme-inhibitor complex. The structure of ribonuclease A, determined by Gopinath Kartha and his colleagues, became available soon afterwards [11]. The structures of many proteolytic enzymes were subsequently determined in quick succession [12]. Towards the end of the decade, in 1969, the much awaited structure of insulin, analysed by Dorothy Hodgkin and her colleagues, became available [13,14].

The sixties also marked the beginning of the efforts to analyse, validate and describe structural data emanating from protein crystallographic studies. The most important of these was undoubtedly the construction of the Ramachandran map [15]. In pursuance of an unfortunate controversy around the structure of collagen, G.N. Ramachandran and his colleagues critically examined the distances between non-bonded atoms in all the available relevant crystal structures. They found that non-bonded atoms can approach each other to distances closer than the sum of the their van der Walls radii. On the basis of detailed analysis, they arrived at two sets of limiting/minimum inter atomic distances between pairs of atoms (C…C, C…N, N…O etc.), one which normally occurs and the other which could occur in extreme circumstances. Ramachandran and his colleagues also realised that the mutual orientation of two adjacent planar peptide units can be completely specified by two torson angles, called ϕ and ψ, about the single bonds at the C^α position connecting the peptides. The ϕ, ψ angles at each C^α position along the polypeptide chain then completely specify the conformation of the protein. Using the limiting distances between non-bonded atoms, referred to earlier, Ramachandran and his colleagues derived the possible values of ϕ and ψ and presented the results in the form of a map. The map was deviced at a time when the first high resolution structure of a protein was just emerging. However, all the protein structures subsequently solved do conform to the Ramachandran map (Figure 2). Indeed, the Ramachandran map remains the simplest descriptor and tool for validation of protein structures.

Globally macromolecular crystallography came of age in the seventies of the last century. Since then the progress in the area has been explosive and was aided by technological and scientific advances. Large synchrotron facilities and position sensitive detectors made data collection fast and efficient. The rapid increase in computing power made data analysis also fast and efficient. The need for large amounts of protein samples for crystallization experiments was met by recombinant technology. Protein engineering techniques allowed crystallographers to explore structure-function relationships in considerable detail. Rapid advances in biochemistry, molecular biology and cell biology provided added impetus to macromolecular crystallographic studies. The large structural genomics or proteomics programmes resulted in structural studies on cassettes of large numbers of proteins. There is hardly any area of modern biology which has not been illuminated by X-ray crystallographic studies [16,17]. Much work had been done in elucidating the structure and function of macromolecular assemblies as well. The largest one is undoubtedly the ribosome structure analysed by Ada Yonath, Venki Ramakrishnan and Thomas Steiz [18].

The Indian Effort. The beginnings and the spread

India has a long tradition in structural crystallography, starting with the work of K. Banerjee at the Indian Association for the Cultivation of Science in Kolkata in the thirties. As indicated earlier, Ramachandran and his colleagues gave a kick start to structural biology in India through their efforts in computational biology, modeling and what we now call bioinformatics. A few Indians, notably Gopinath Kartha, have also been involved in macromolecular crystallographic projects abroad. However, I was the first trained protein crystallographer to return to India, to the Indian Institute of Science (IISc), Bangalore in 1971, after participating in the structure solution of insulin in the laboratory of Dorothy Hodgkin at Oxford. I would have liked nothing better than to initiate macromolecular crystallography at that time, but circumstances were not propitious for doing so. In particular, funds available for research were meager. Therefore, I initiated a programme involving preparation and X-ray analysis of crystalline complexes of amino acids and peptides among themselves as well as with other molecules. In addition to efforts on non-steriodal anti-inflamatory drugs and ionophores, this programme was the mainstay of the of the laboratory, particularly after realising the implications of the results for chemical evolution and origin of life. The results were also of interest in relation to what we now describe as supramolecular association. In the meantime, K.K. Kannan, who was involved in the structure solution of carbonic anhydrase at Upsala, Sweden returned to the Bhabha Atomic Research Centre (BARC) in 1978.

Macromolecular crystallography in India received the first major impetus when the Department of Science and Technology (DST) generously funded our group at Bangalore in 1983 as part of their Thrust Area Progamme. It was also understood that the Bangalore centre would function as a national nucleus for the development of the area in the country. Since then, the area spread across the country. Work in the area is now pursued in about 30 institutions in India, led substantially be scientists trained at Bangalore or their descendents (Figure 3). The effort now receives generous support not only from DST, but also from other agencies such as the Department of Biotechnology (DBT) and the Council of Scientific and Industrial Research (CSIR), and encompasses a wide spectrum of protein studies [19]. Macromolecular crystallographic studies have indeed become an integral part and important component of modern biological research in the country.

Structures, Mechanisms and Functions

The early macromolecular efforts in the country have been concerned primarily with lectins, plant viruses and protein hydration at Bangalore and carbonic anhydrase at Mumbai, to be followed soon by those on proteins in animal secretions at the All India Institute of Medical Sciences (AIIMS), New Delhi, and on protease inhibitors at the Saha Institute of Nuclear Physics (SINP), Kolkata (Figure 4). In particular, crystallography of lectins played a major role in the early development of the area in India. Work at Bangalore on lectins was initiated at a time when the importance of protein-sugar interactions in recognitive processes was being increasingly recognized. Lectins are found in all forms of life and can assume widely different folds and oligomeric states. The efforts at Bangalore have encompassed four of the five structural classes of plant lectins. In fact, one of them was first identified at Bangalore. It was demonstrated that three of these classes constitute families in which small alterations in essentially the same tertiary structure lead to large variations in quaternary association. The general problems of quaternary association and ligand specificity received special attention in the lectin programme at Bangalore. In particular, water-bridges, post-translational modification, differences in loop length and oligomerisation were identified as strategies for generating ligand specificity. The work on lectins at Bangalore has recently been expanded to include those from mycobacteria as well. Significant contributions to the structural biology of lectins have emanated also from AIIMS, the National Chemical Laboratory (NCL), Pune and the Kannur University. Recently work in the area has been initiated at the Indian Institute of Advanced Research, Gandhinagar as well.

The work at Bangalore on two plant viruses, Sesbania Mosaic Virus (SMV), Physallis Mottle Virus (PhMV), initiated in the eighties and pursued subsequently on a long term basis, is among the milestones in the development of structural biology in India. Viruses are among the largest objects addressed using X-ray crystallography and the solution of the two virus structures using the meager facilities then available, is a remarkable achievement. Furthermore, work on them over the decades, among other things, led to important insights into virus assembly. In another effort at Bangalore, protein hydration and its consequences were explored using primarily water-mediated transformations in which protein crystals undergo reversible transformations when the water content of the crystals is altered. This effort led to the identification of a relation among hydration, mobility and protein action. In particular, structural changes that accompany partial dehydration appeared to mimic those that occur during protein action. The work also established partial dehydration as a means for improving crystal quality.

The early efforts at BARC, Mumbai were concerned with carbonic anhydrase with emphasis on complexes with sulfonamides, metal ions etc. with a view to elucidating the mechanism of action of the enzyme. Another early work at BARC was on the ribosome inactivating protein, gelonin.

A major macromolecular crystallographic group which emerged in the nineties and continues to be very productive is at AIIMS. The work at AIIMS encompasses many different areas. One major area of research is concerned with proteins in animal, including human, secretions. The proteins include lactoferrins, lactoperoxidases, peptidoglycan recognition proteins, mammary gland/breast cancer regression proteins and matrix melanosomal proteins. Much of the work at AIIMS has a pronounced medical orientation. The AIIMS group has also addressed specific drug targets such as phospholipase A2, cycloxygenases, lipoxygenases, endothelin receptor etc. Their effort at structure-based inhibitor/drug design is well-known. Another important protein studied by them is bacterial hyaluronidase lyases.

Studies on proteases and their inhibitors are being pursued in several laboratories. Macromolecular crystallographic work at SINP, Kolkata started with structural studies on proteinaceous inhibitors of serine proteases. Work on protease inhibitors has been carried out at AIIMS, Indian Institute of Technology, Roorkee and NCL as well. Work at SINP now encompasses a major, multi-pronged effort on cysteine proteases. Another laboratory where substantial work on proteases has been carried out is the one at the Madras University at Chennai. Sequence dependence of the structure of DNA has also been crystallographically investigated at the University. Structural studies of hemoglobin from a variety of sources have also emanated from Chennai. A major interesting recent contribution from the University has been the structure analysis of jack bean urease, the first enzyme to be crystallized decades ago.

A major long term programme which has yielded rich dividends is on molecular mimicry carried out the National Institute of Immunology (NII) at New Delhi. The programme started with the design and development of peptide mimics for sugars which interact with carbohydrate binding proteins. It went on to encompass major fundamental issues such as antibody maturation and the structural basis of allergy.

A major crystallographic effort at the Centre for Cellular and Molecular Biology (CCMB), Hyderabad is concerned with poof reading during translation. Proof reading operates at different levels and involves, for instance, discrimination between L- and D-amino acids as well as between amino acids with the same chirality but very similar structure. The work at CCMB has provided important insights into the mechanism of proof reading during translation. The work at the centre has also encompassed bacterial lipase and crystallins. An interesting contribution to emerge from the Bose Institute, Kolkata has been the structure of λCII. The only structure of a membrane protein to emerge from India has been that of OmpC from the Madurai Kamaraj University.

Perhaps the first bacterial protein to be X-ray analysed in India was uracil DNA-glycosylase from *E.coli* at Bangalore. The Bangalore effort on microbial xylanases has been also noteworthy. In yet another effort NCL has been involved in structural studies penicillin V acylase and hydrolase.

Structural Biology of Microbial Pathogens

By the turn of the century, macromolecular crystallography in India had acquired a reasonable level of maturity and time was ripe to explore problems of immediate relevance to the country. Infectious diseases are particularly relevant for comparatively poor countries. Therefore, there was a conscious decision to pursue the structural biology of microbial pathogens. In particular, a concerted effort developed on mycobacterial, particularly TB, proteins. The determination of the sequence of the *M. tuberculosis* genome in the nineties provided further impetus to this effort. Although there have been a modeling study of a TB protein and an outstanding annotation of a *M. tuberculosis* gene earlier, the first crystallographic analysis of a TB protein in India was that on *M. tuberculosis* RecA at IISc, Bangalore, published in 2000. The Bangalore group also joined an international TB structural genomics consortium which was started around the same time. Since then structural work on mycobacterial proteins were initiated and are being pursued at several institutions including the Institute of Microbial Technology, Chandigarh; Centre for DNA Fingerprinting and Diagnostics, Hyderabad; NII, New Delhi; Central Drug Research institute, Lucknow; CCMB, Hyderabad; Indian Institute of Technology, Kharagpur;

Indian Institute of Technology, Kanpur; Institute of Genomics and Integrated Biology, New Delhi; and the Delhi University.

Those emanating from Indian laboratories account for more than 10% of the number of TB protein structures determined internationally. The proteins analysed in India cover a broad spectrum such as those involved in DNA replication, recombination, repair and modification; transcription and translation; amino acid synthesis, degradation and modification; fatty acid, myolic acid and petidoglycan synthesis; biosynthesis of cofactors, prosthetic groups and carriers, and signalling. In some instances, structures of homologous proteins from other mycobacteria such as *M. smegmatis* have also been determined. For example, RecA from *M. tuberculosis* and *M. smegmatis* and their mutants have been studied extensively under different environmental conditions and in complex with different ligands. Likewise, structures of single stranded DNA binding protein from *M. tuberculosis* and *M. smegmatis* and *M. leprae* have been determined in different crystal forms. Structural results on mycobacterial proteins that have emanated from different laboratories have been of general interest in elucidating many biochemical mechanisms, in addition to illuminating features specific to mycobacteria. The structures analysed so far include those of many proteins essential for the survival of the organism. Indeed, the extensive results obtained from structural studies in India on mycobacterial proteins form a platform for structure-based inhibitor design. Some efforts in this direction have already been initiated.

Another bacterial pathogen, the structural biology of which is being pursued in more than one laboratory in India is *Salmonella typhimurium*. Significant contributions on the structure and function of *S. typhimurium* proteins have emerged from IISc, IMTech and BARC. Malaria is a major problem in India, as indeed in many other countries. The structural biology efforts at the

International Centre for Genetic Engineering and Biotechnology, New Delhi is almost wholly concerned with proteins from this parasite. These efforts targets a spectrum of proteins from the malarial parasite. Work on the proteins from the parasite is being pursued at IISc, Bangalore as well. *Leishmania donovani* is a pathogen of special interest to India. Structural work on *L. donovani* proteins is in progress at SINP and CDRI. *Entamoeba histolytica* is a widespread pathogen and structural studies on proteins from this organism is in progress at the Jawaharlal Nehru University, New Delhi. Work on proteins from the organism has been initiated at IISER, Bhopal as well.

Work on two plant viruses at IISc, Bangalore has already been referred to. Rotavirus is a human pathogen, proteins from which are studied at Bangalore. Another major effort pertaining to a virus is that on a tethered mutant of HIV protease being carried out at BARC, Mumbai. Extensive structural studies on this mutant have yielded important information on many aspects of the protein, including the development of drug resistance.

Structural studies on proteins from microbial pathogens are expected to lead to serious efforts in structure based drug and vaccine development. Efforts on drug development should be preceded by extensive studies on inhibitor design. When a large number of inhibitors are developed as lead compounds, one or more might turn into a drug candidate. Individual initiative and open ended research are necessary for developing lead compounds. Once a drug candidate is identified, then highly organized, tightly controlled efforts would be necessary. The current paradigm of drug development which is substantially based on identification of individual targets and their inhibitors, appears to have reached the state of diminishing returns. It is therefore important to explore new holistic paradigms of drug design. Indeed, it is good fundamental research and a prepared mind that might lead to drugs and vaccines. We also need to be conscious of the need for combating the pathogens on a long term basis. Several decades ago, with the advent of antibiotics, we had the illusion of being on the way to conquering infectious diseases. However, pathogens rapidly developed drug resistance thus necessitating the development of newer drugs. Therefore the fight against pathogens needs a constant long term effort. In order to combat any evolving pathogen on a long term basis, we need to know well the basic biology of the organism. Contribution to this knowledge is again a major objective of structural studies on microbial pathogens.

Conclusion

Macromolecular crystallography has now developed into an important component of biological research in the country. Macromolecular NMR studies, the other approach for determining protein structures, are now gathering momentum in India. Computational biology, including modeling and what we now call bioinformatics had a head start in the country, thanks to the pioneering efforts of G.N. Ramachandran and his colleagues. Work in the area went through a trough for reasons that need not be gone into here, but is now in a resurgent phase. Thus, structural biology in India is in a reasonable state of health. Yet, in terms of global impact, we are yet to reclaim the heights which G.N. Ramachandran conquered decades ago. However, the quality and the quantity of the current efforts in the area by younger colleagues in different laboratories give reason to believe that we would do so in the none-too-distant future.

Acknowledgments: I thank M. Selvaraj and Pankaja C. for help in preparation of the manuscript

References *

1. Bernal JD, Crowfoot D (1934) X-ray photographs of crystalline pepsin. Nature 133: 794-795

2. Crowfoot D (1935) X-ray single crystal photographs of insulin. Nature 135: 591-592

3. Bernal JD, Fankuchen I, Perutz MF (1938) An X-ray study of chymotrypsin and haemoglobin. Nature 141: 523-524

4. Pauling L, Corey RB, Branson HR (1951) The structure of proteins: Two hydrogen-bonded helical configurations of polypeptide chain. Proc. Natl. Acad. Sci. USA 37: 205-211

5. Pauling L, Corey RB (1951) The pleated sheet. A new layer configuration of polypeptide chains. Proc. Natl. Acad. Sci. USA 37: 251-256

6. Watson JD, Crick FHC (1953) Molecular structure of nucleic acids. A structure for deoxyribose nucleic acid. Nature 171: 737-738

7. Ramachandran GN, Kartha G (1955) Structure of collagen. Nature 176: 593-595

8. Kendrew JC, Dickerson RE, Strandburg BE, Hart RG, Davies DR, Phillips DC, Shore VC (1967) Structure of myoglobin. A three-dimensional Fourier synthesis at 2 Å resolution. Nature 185: 422-427

9. Perutz MF, Rossmann MG, Cullis Ann F, Muirhead H, George W, North ACT (1960) Structure of Hemoglobin. A three dimensional Fourier synthesis at 5.5 Å resolution. Nature 185: 416-422

10. Blake CCF, Koenig DF, Mair GA, North ACT, Phillips DC, Sarma VR (1965) Structure of hen egg white lysozyme: A three dimensional Fourier synthesis at 2 Å resolution. Nature 206: 757-761

11. Kartha G, Bello J, Harker D (1967) Tertiary structure of ribonuclease. Nature 213: 862-865

12. Phillips D, Blow D, Hartley B, Dowe G. (1970) Phil. Trans. Royal Soc. London Series B 257: 63-266

13. Adams MJ, Blundell TL, Dodson EJ, Dodson GG, Vijayan M Baker EN, Harding MM, Hodgkin DC, Rimmer B, Sheat S (1969) Structure of rhombohedral 2 Zinc insulin crystals. Nature 224: 491-495

14. Blundell TL, Cutfield JF, Dodson EJ, Dodson GG, Hodgkin DC, Mercola DA, Vijayan M. (1971) Atomic positions in rhombohedral 2 zinc insulin crystals. Nature 231: 506-511

15. Ramachandran GN, Ramakrishnan C and Sasisekharan V (1963) Stereochemistry of polypeptide chain configurations. J. Mol. Biol. 7: 95-99

16. Liljas A, Liljas L, Piskar J, Lindblom G, Nissen P, Kjeldgaard (2009) Text book of Structural Biology, World Scientific Publishing Co., Singapore

17. Berman HM, Battistuz T, Bhat TN, Bluhm W, Bourne PE, Burkhardt K, Feng Z, Gilliland GL, Iype L, Jain S, Fagan P, Marvin J, Padilla D, Ravidhandran V, Schneider B, Thanki N, Weissig H, Westbrrok JD, Zardecki C. (2002) The Protein Data Bank. Acta Cryst D58, 899-907

18. Ramakrishnan V (2002). Ribosome structure and the mechanism of translation. Cell 108, 557-572

19. Vijayan M (2007) Macromolecular crystallography in India. A historical overview. J. Indian Inst. Sci. 87: 261-277

20. Vijayan M (2013) The legacy of G.N. Ramachandran and the development of structural biology in India, In: Bansal M, Srinivasan N (eds). Biomoleuclar forms and functions, IISc Press, World Scientific, Singapore, pp 1-16

21. Vijayan M, Johnson LN (2005) Gopalasamudram Narayana Ramachandran 8 October 1922-7 April 2001: Elected FRS 1977. Biogr. Mems. Fell. R. Soc. 51: 367-377

22. Banerjee R, Shekhar SC, Ganesh V, Kalyan Das, Dhanraj V, Mahanta SK, Surolia A, Suguna K, Vijayan M. (1994) Crystal structure of peanut lectin, a protein with an unusual quaternary structure. Proc. Natl. Acad. Sci. USA 91: 227-231

23. Banerjee R, Das K, Ravishankar R, Suguna K, Surolia A, Vijayan M (1996) Conformation, protein-carbohydrate interactions and a novel subunit association in the refined structure of peanut lectin lactose complex. J. Mol. Biol. 259: 281-296

24. Sankaranarayanan R, Sekar K, Banerjee R, Sharma V, Surolia A, Vijayan M (1996) A novel mode of carbohydrate recognition in jacalin, a Moraceae plant lectin with a β-prism fold. Nat. Struc. Biol. 3: 596-603.

25. Chandra NR, Ramachandraiah G, Bachhawat K, Dam TK, Surolia A, Vijayan M (1999) Crystal structure of a dimeric mannose specific agglutinin from garlic: Quaternary association and carbohydrate specificity. J. Mol. Biol. 285: 1157-1168

26. Madhusudan, Kodandapani R, Vijayan M. (1993) Protein hydration and water structure: X-ray analysis of a closely packed protein crystal with very low solvent content. Acta Cryst. D49: 234-245.

27. Sri Krishna S, Hiremath CN, Munshi SK, Sastri M, Savithri HS, Murthy MRN (1999) Three dimensional structure of physallis mottle virus: Implications for viral assembly. J. Mol. Biol. 289: 919-934

28. Bhuvaneswari M, Subramanya HS, Gopinath K, Nayudu MV, Savithri HS, Murthy MRN (1995) Structure of sesbania mosaic virus at 3.0 Å resolution. Structure 3: 1021-1030

29. Chakravarthy S, Kannan KK (1994) Drug-Protein interactions: refined structures of three sulfonamide drug complexes of human carbonic anhydrase I enzyme. J. Mol. Biol. 243: 298-309

30. Sharma AK, Paramasivam M, Srinivasan A, Yadav MP, Singh TP (1999) Three-dimensional structure of mare diferric lactoferrin at 2.6 Å resolution. J. Mol. Biol. 289: 303-317

31. Ravichandran S, Sen U, Chakrabarti C, Dattagupta JK (1999) Cryocrystallography of a Kunitz-type serine protease inhibitor: the 90 K structure of winged bean chymotrypsin inhibitor (WCI) at 2.13 Å resolution. Acta Cryst. D55: 1814-1821

* During the past couple of decades, hundreds of proteins structures have been determined in Indian laboratories which have been described in hundreds of research publications. Only ten references representing the early efforts are listed here. A complete list of macromolecular crystallographic publications that have emanated from India till 2010 is given in http://mbu.iisc.ernet.in/~mvlab/history.html

Figure 1. Perpendicular views of a schematic representation of a few turns of collagen. Reproduced from Ref. 20

Figure 2. Ramachandran map generated from 21 selected high resolution structures. Reproduced from Ref. 21

Figure 3. Institutions where macromolecular crystallographic studies were initiated before 1981 (sky blue), during 1981-91 (red), during 1991-2001 and since 2001. Reproduced from Ref. 20

Figure 4. Examples of crystal structures of proteins determined in India during the nineteen nineties. (a) peanut lectin (PDB code 2PEL) [22,23] (b) subunit and tetramer of jacalin (1JAC) [24], (c) garlic lectin (1KJ1) [25], (d) close packing in a low humidity form of monoclinic lysozyme (reproduced from Ref. 26), (e) structures of physallis mottle virus and sesbania mosaic virus (figures kindly made available by M.R.N. Murthy) [27,28], (f) a complex of human carbonic anhydrase with a sulfonamide drug (1AZM) [29], (g) diferric mare lactoferrin (1B1X) [30], and (h) a chymotrypin inhibitor from winged beans (4WBC) [31]

Figure 1
Click here to download colour figure: Figure1.pptx

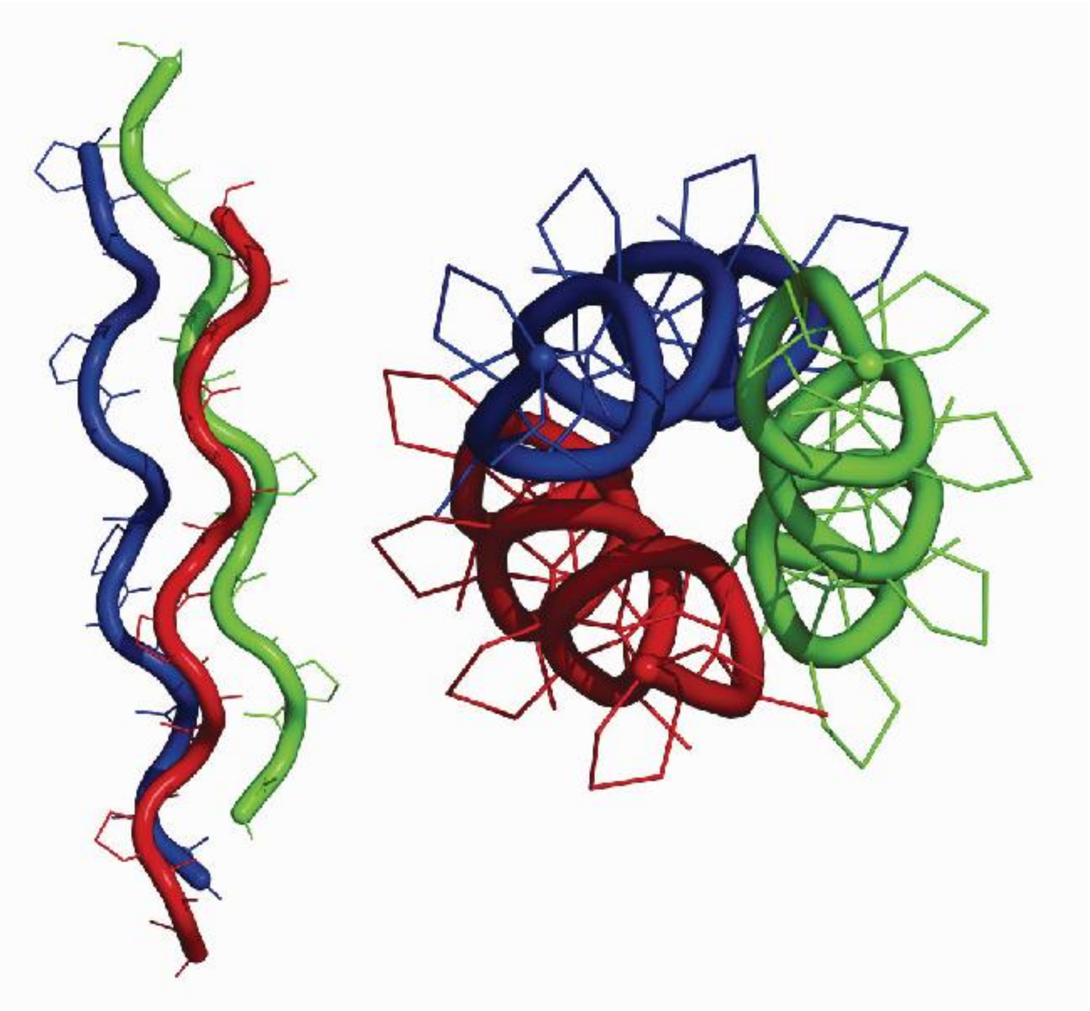

Figure 1

Figure 2

Click here to download colour figure: Figure2.pptx

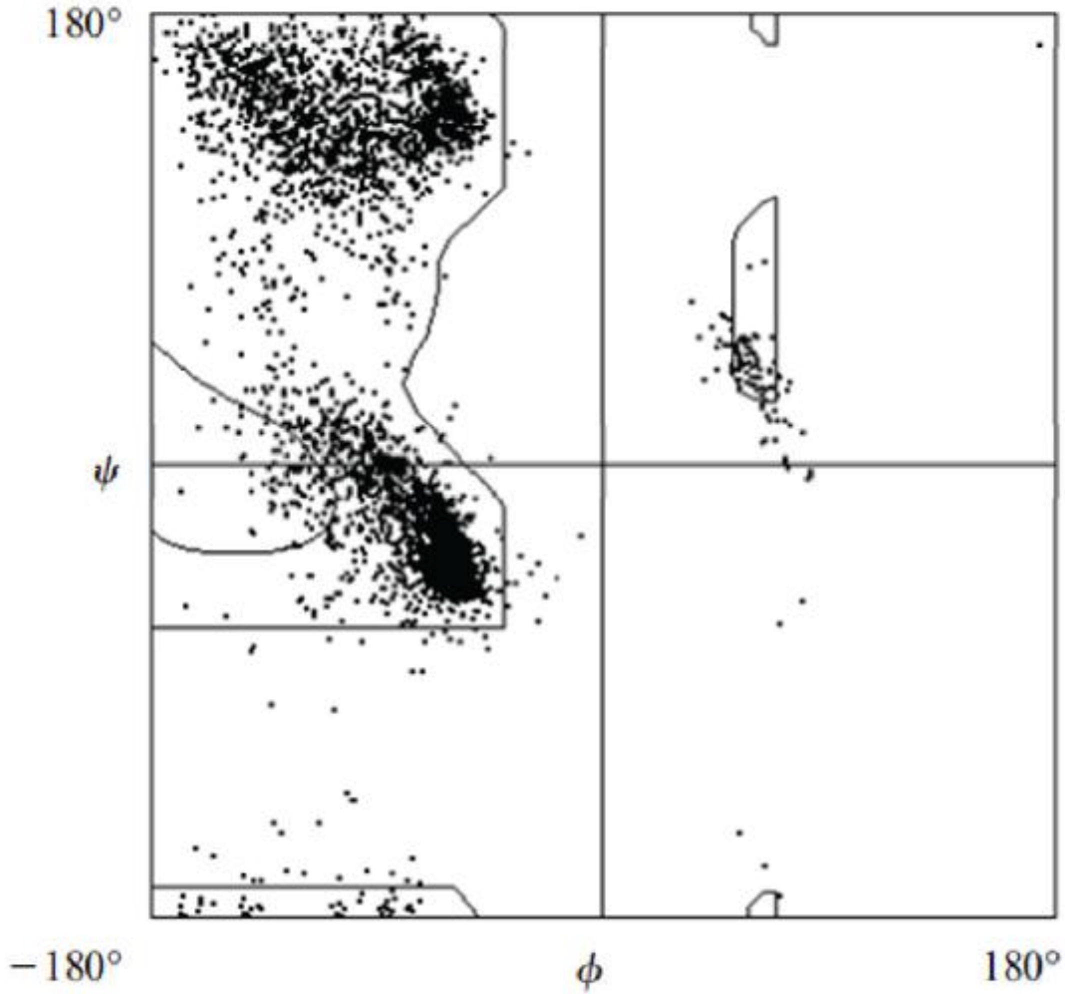

Figure 2

Figure 3

Click here to download colour figure: Figure3.pptx

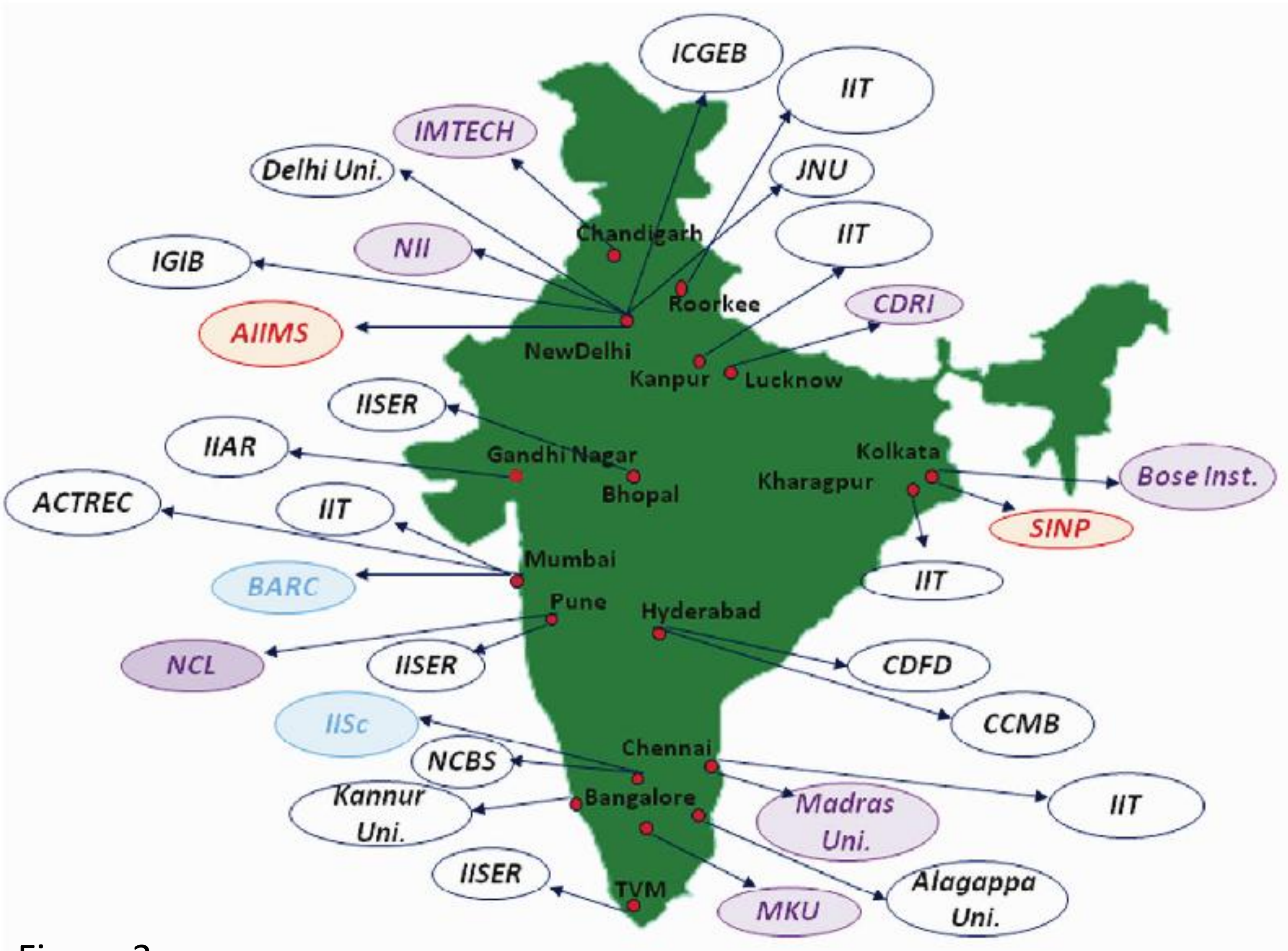

Figure 3

Figure 4a
Click here to download colour figure: Figure4a.pptx

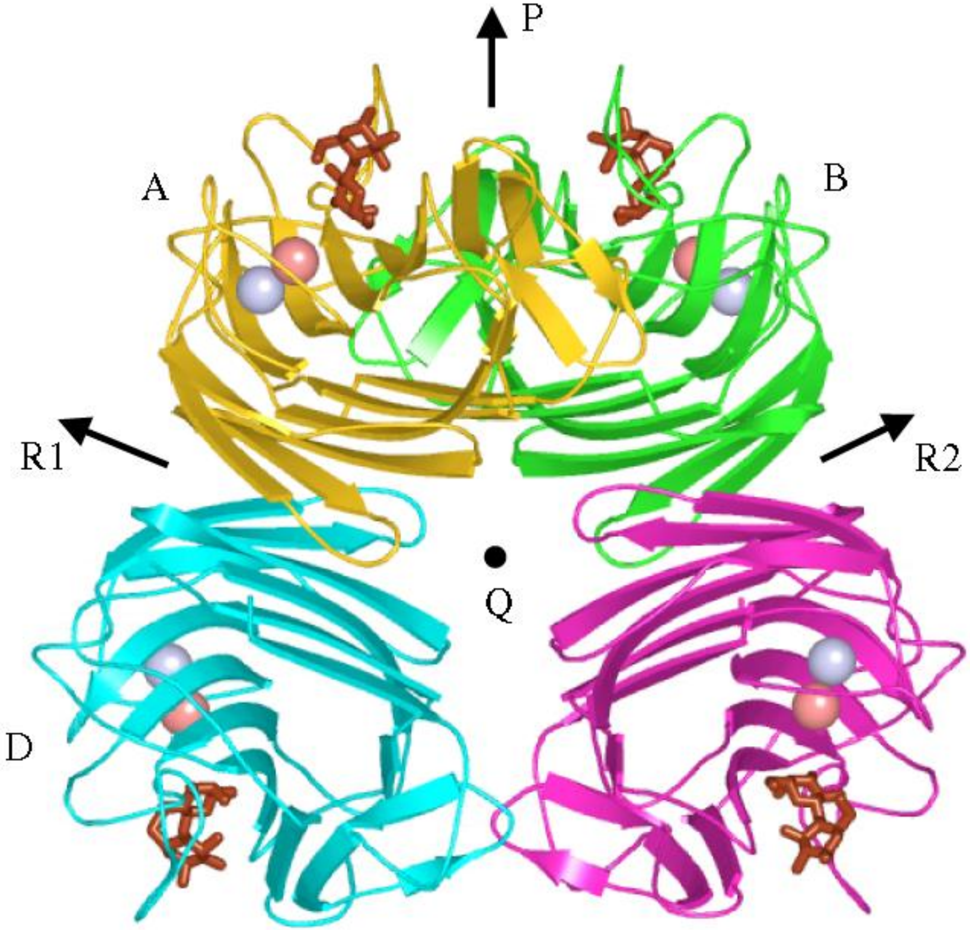

Figure 4a.

Figure 4b
Click here to download colour figure: Figure4b.pptx

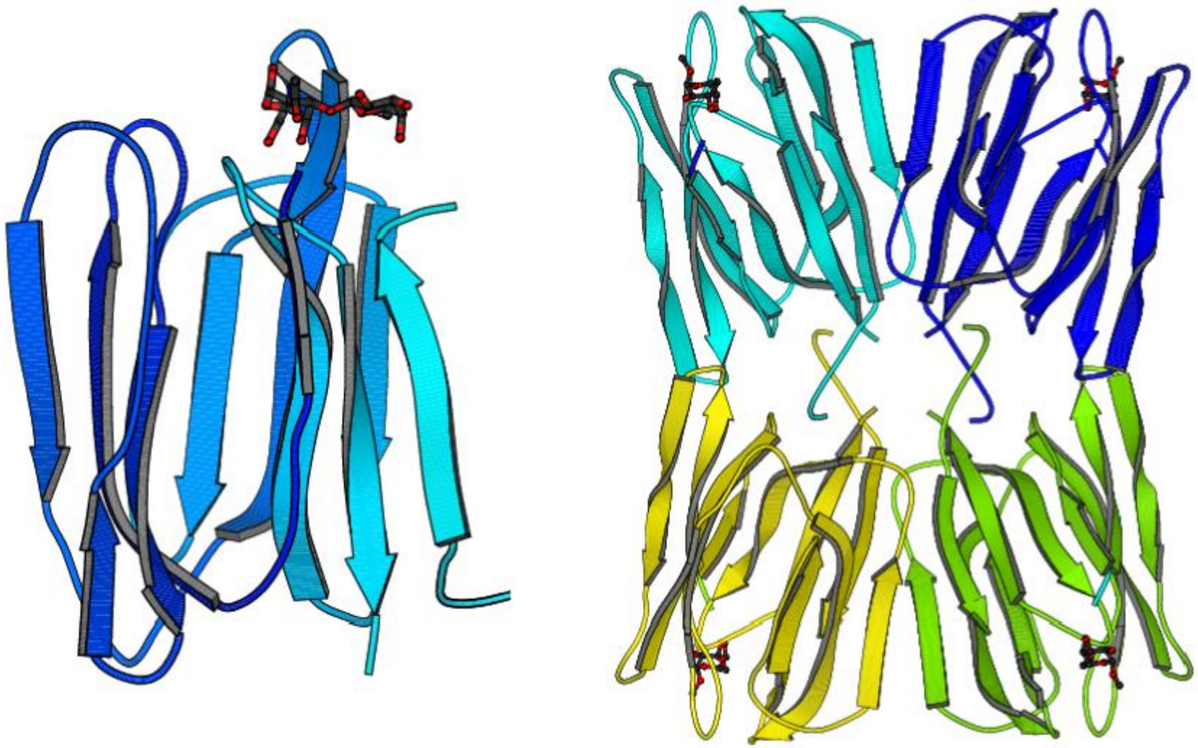

Figure 4b.

Figure 4c

Click here to download colour figure: Figure4c.pptx

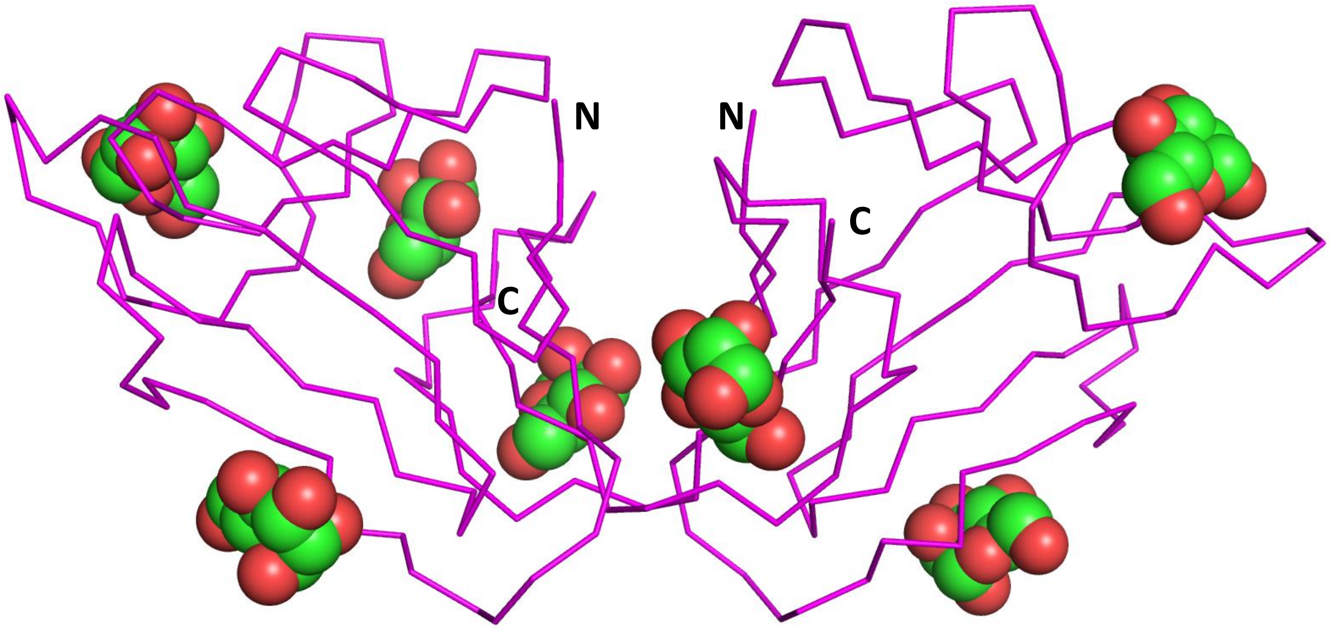

Figure 4c.

Figure 4d

Click here to download colour figure: Figure4d.pptx

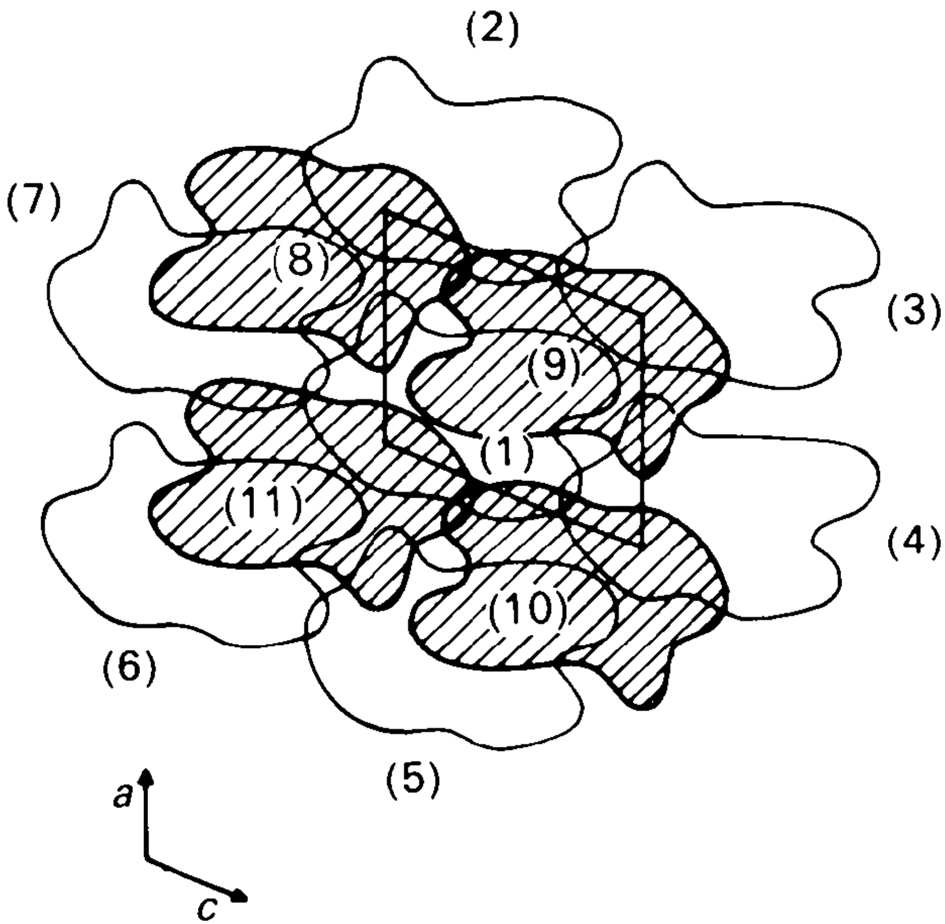

Figure 4d.

Figure 4e
Click here to download colour figure: Figure4e.pptx

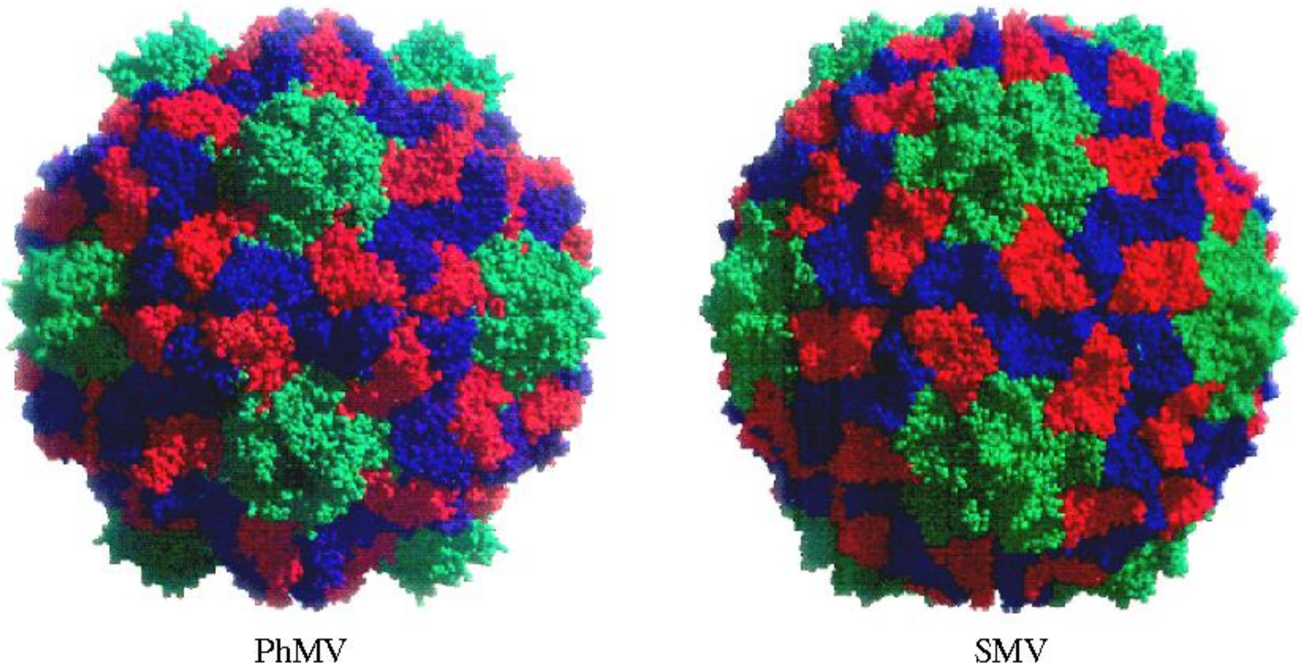

Figure 4e.

Figure 4f
Click here to download colour figure: Figure4f.pptx

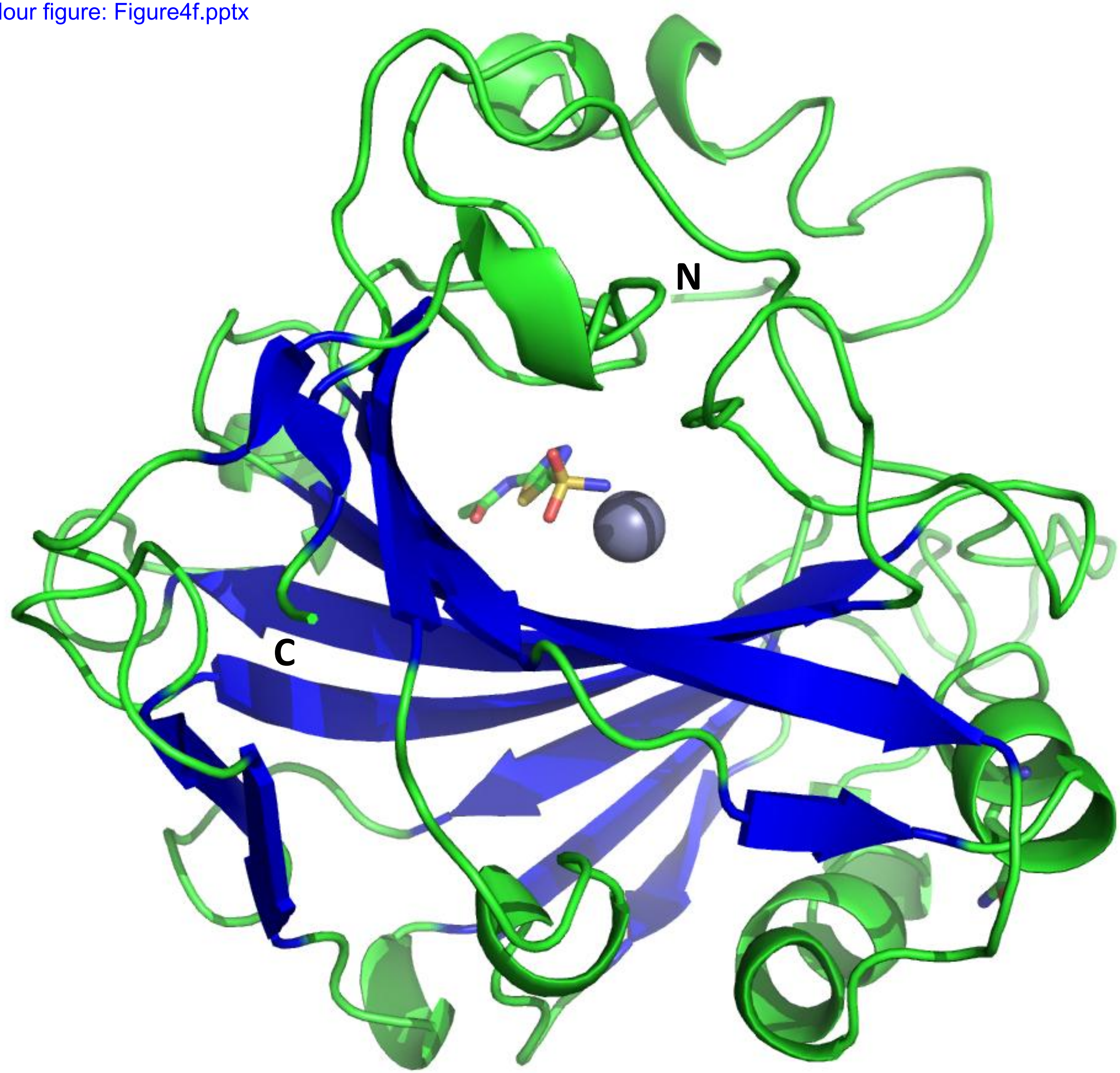

Figure 4f.

Figure 4g
Click here to download colour figure: Figure4g.pptx

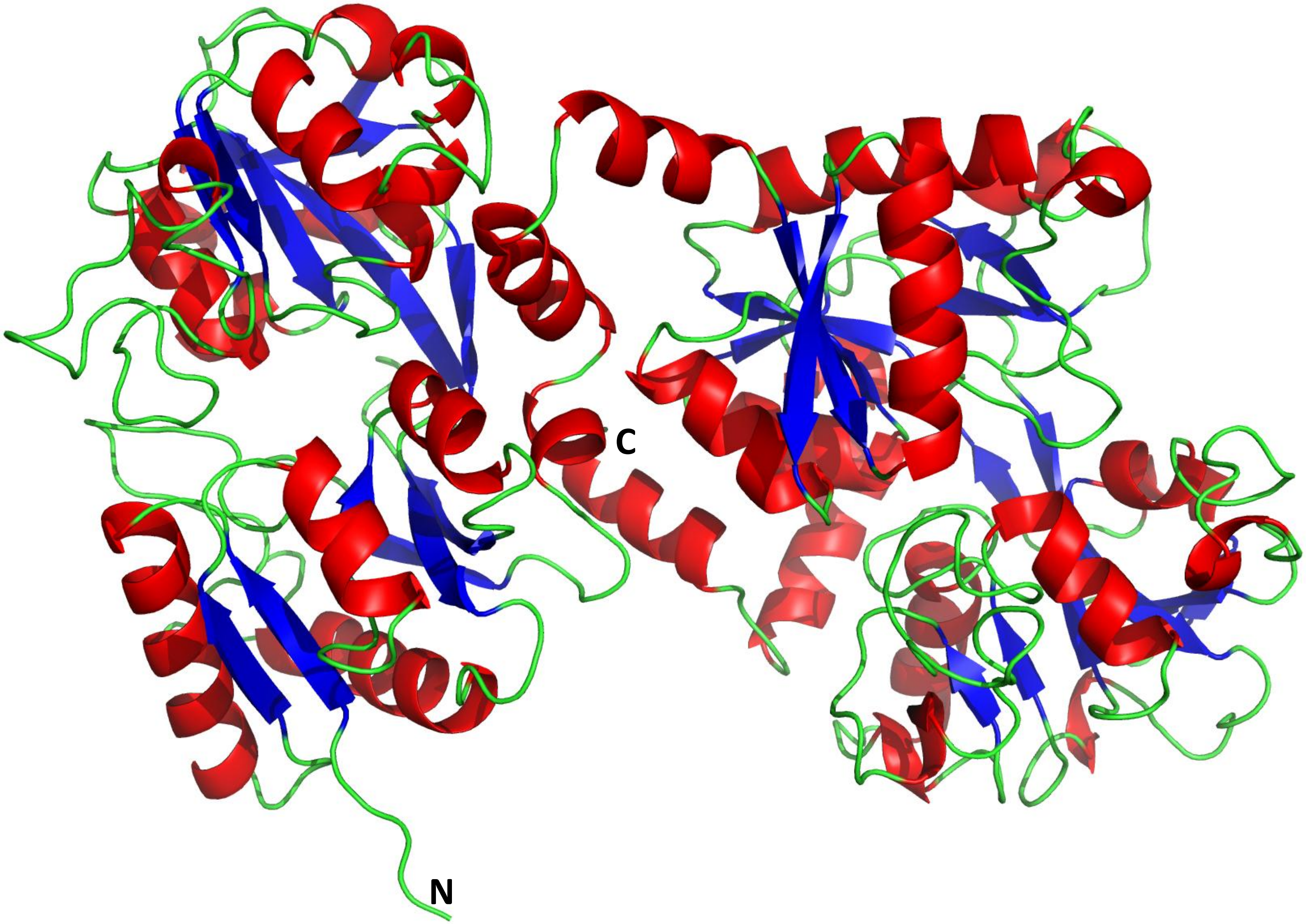

Figure 4g.

Figure 4h

Click here to download colour figure: Figure4h.pptx

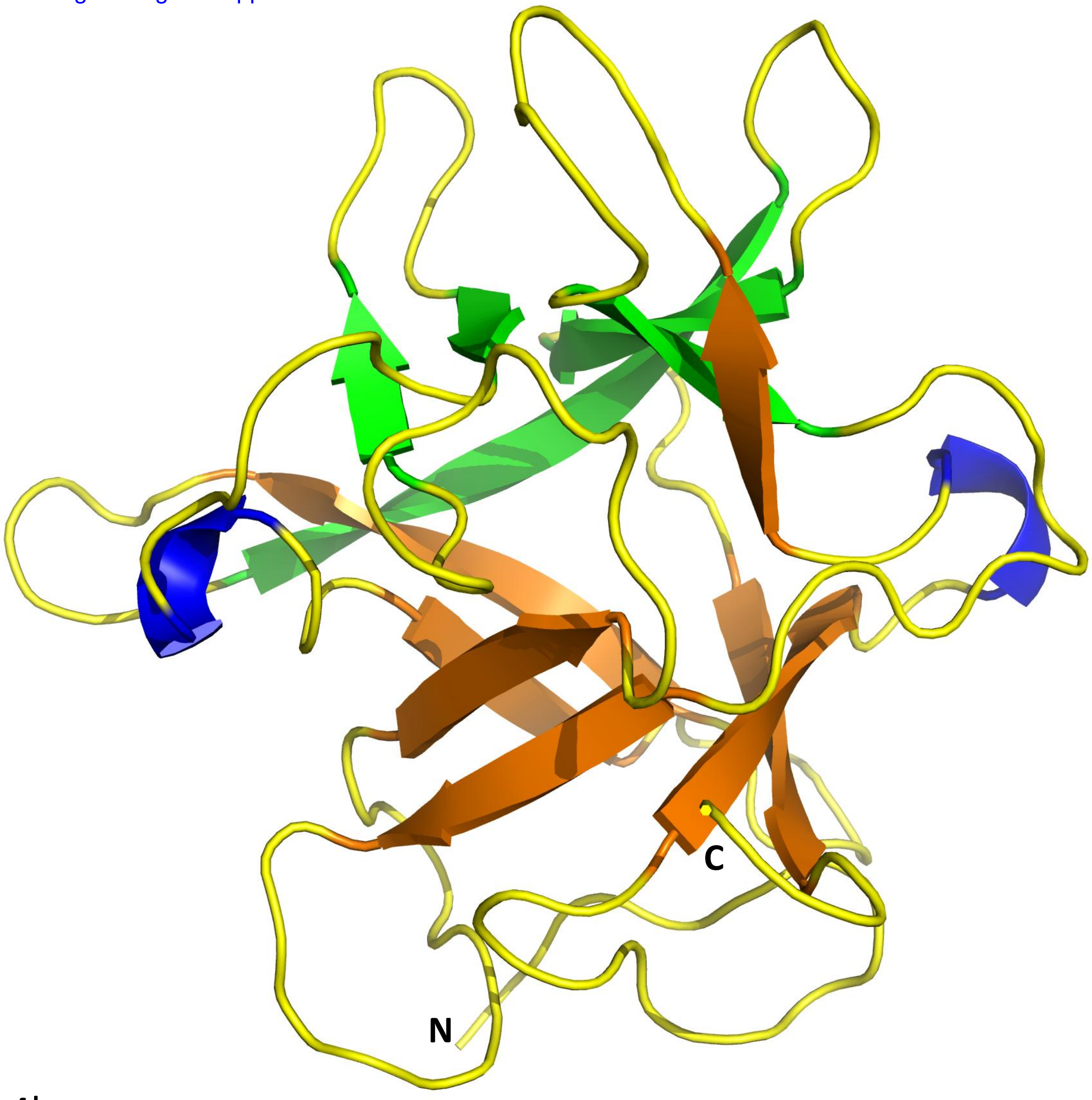

Figure 4h.