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D. K. GHOSH

Geology Department
Lucknow University
Lucknow 226 001, India

P. L. Narula and S. K. Shome reply:

The part picked up by the discussor from the paper is from the discussion part wherein the behaviour and the patterns of the isoseismals have been sought to be explained by relating to the possible source mechanisms. The paper, as is explicit from the title, pertains to a review on the macroseismic studies and does not purport to be a critique on seismotectonic models or seismotectonic studies. However, we have attempted to explain the anomalous behaviour of the attenuation and accentuation patterns with the possible genetic relationships in consonance with the prevalent tectonic setting and, thus the allegation that 'it is incomplete, no new ideas are presented and rather repeats old views without any reference, hence it is a borrowed idea' is not warranted.

For intersection tectonics no claim has been made for it to be an original idea and in fact reference has been made to Talwani (1989). We are happy to note that the discussor had arrived at similar views from an integrated study of morphotectonic setting and Quaternary fluvial regime of the western Himalaya.

P. L. NARULA
S. K. SHOME

Geological Survey of India
Lucknow 226 001, India

RESEARCH NEWS

Materials with negative Poisson's ratio

G. S. Ranganath

It is a matter of common experience that solids when stretched in a particular direction suffer a contraction in the lateral direction. The ratio of lateral strain of contraction to longitudinal strain of extension is the Poisson's ratio, σ. It is always a constant for a given material. Most solids have a positive Poisson's ratio. Interestingly, the physics of elastic bodies does not impose any restrictions on the sign of σ. When a solid is stretched in one direction it can also expand in the perpendicular direction (see Figure 1). For isotropic materials it has a lower bound of -1 and an upper bound of $+1/2$. At $\sigma = -1$ the material has infinite rigidity modulus and at $\sigma = +1/2$ the material has infinite bulk modulus. It therefore intrigued many, including Poisson, that a large class of materials should have only a positive Poisson's ratio. Poisson himself came up with a molecular model that lead to $\sigma = +1/4$. In this model an assembly of spheres interact only along the line joining the centres with no force required for tangential displacements. This triggered an extensive search for materials with negative σ. The lowest value of σ was reported by Poisson himself in the case of cork ($\sigma \approx 0$). Poisson argued that bottle stoppers made of cork can be cylindrical in shape due to σ of cork being nearly zero. They will not laterally expand when axially compressed. On the other hand, it is nearly impossible to push in, through a bottleneck, a cylindrical stopper made of rubber since its σ is close to 0.5. Hence the stopper has to be of a tapered conical form. In the beginning, workers in this field confined themselves to looking at isotropic solids and without a single exception they all had positive σ. It was in the world of crystals that they had some success in finding negative Poisson's ratio. Here again a majority of crystals had a positive σ but a limited number of them exhibited negative σ. Single crystals of zinc and ammonium dihydrogen phosphate are examples of this rare class[1]. It must be remarked that both these are anisotropic crystals and negative σ is observed only for certain directions of axial strain. However, Love[2] mentions a single example of a cubic crystal of pyrite with $\sigma = -0.14$. He suggested that this negative value may have resulted from crystal twinning.

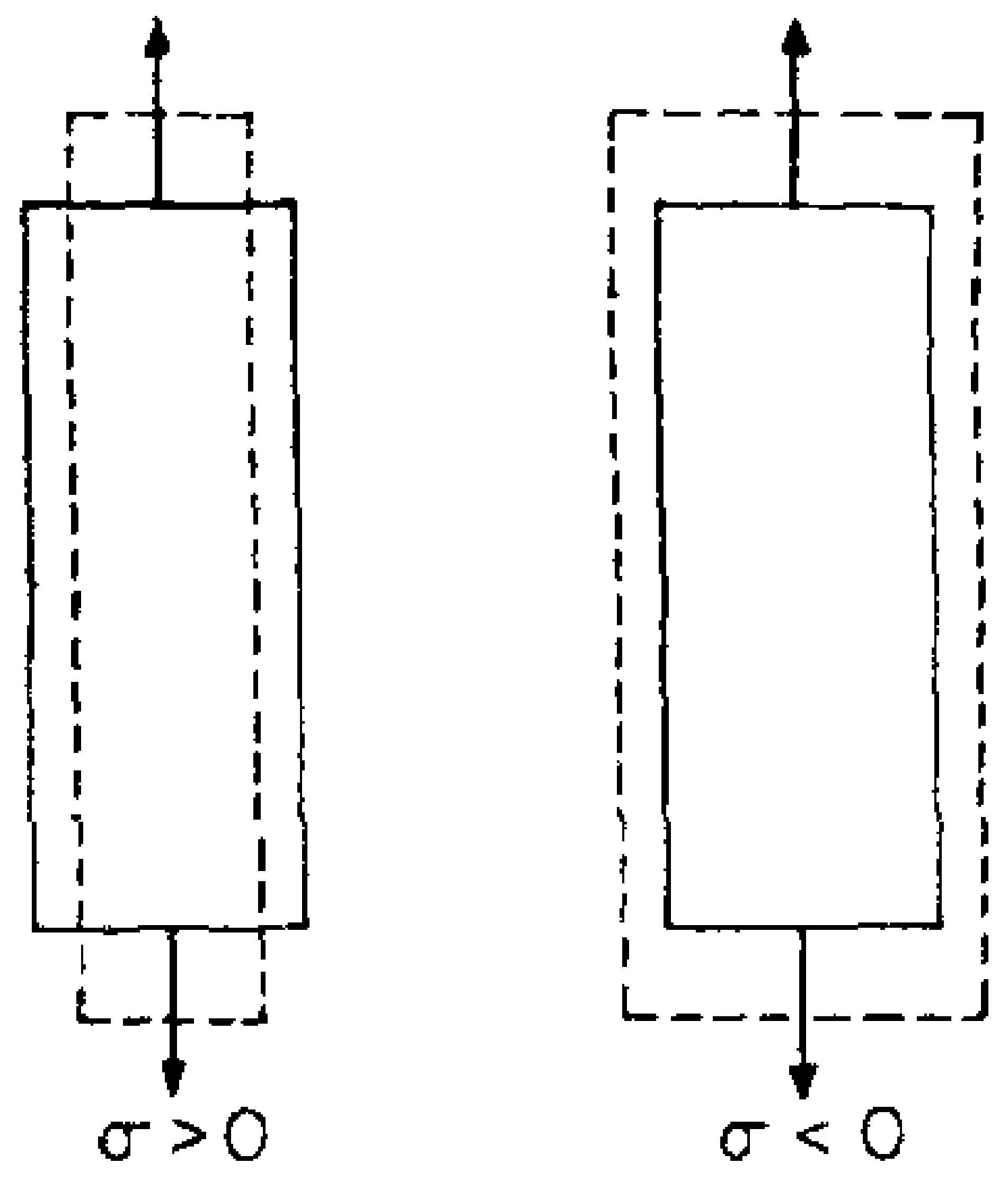

Figure 1. Effect of uniaxial tension on a strip of an isotropic material. The deformed structure is indicated by the dotted line.

It is against such a background that the recent paper in *Nature*[3] on 'Microstructure of isotropic materials with negative Poisson's ratio' by Rothenburg *et al.* assumes some significance. The authors have undertaken an *engineering* analysis of the problem. They were inspired in this exercise by the work of Lakes[4] on foams. Lakes produced, by a special process, foams of negative Poisson's ratio from conventional low-density open-cell polymer foams, which in their natural state have positive σ like any other isotropic material. Lakes subjected this normal foam to a triaxial compression, i.e. equal compression in three perpendicular directions and heated the foam to a temperature slightly above its softening temperature. The mold was then cooled to room temperature. This foam had undergone a compression by a factor of 1.4 to 4. Lakes found such compressed foams to exhibit negative Poisson's ratio. He got consistent results with foams made of different polymers and having different cell sizes. Interestingly reticulated metal foams transformed by plastic deformation at room temperature also exhibited negative σ. This unusual behaviour of compressed foams was traced to their unusual cell structure—described as *reentrant structure* by Lakes. An example of such a reentrant cell is shown in Figure 2. This was obtained by a symmetrical collapse of a 24-sided polyhedron of cubic symmetry. A tension applied to the vertical links of such a structure will lead to cell unfolding and lateral expansion, i.e. negative Poisson's ratio. Study of the compressed foams under an optical microscope indicated the existence of such cells with ribs protruding into the cell.

In essence, the work of Rothenburg *et al.* is an elaboration of this interesting idea of *reentrant* cells. They have suggested other possible types of structural units that lead to a negative Poisson's ratio. The common feature of all these structural elements is that they have a very low *axial stiffness* (akin to Young's modulus y) compared to *tangential stiffness* (rigidity modulus n). This is rather understandable because the continuum theory of elasticity of isotropic bodies leads to the relation $\sigma = (y - 2n)/(y + 2n)$. This implies that y should be less than $2n$ for σ to be negative. In a simpler language this can be interpreted to mean that it is far easier to stretch or compress the structural element than shear it. Often this is stated differently to mean that if the elements of a structure are rigid as regards their shape but flexible as regards their size, then an isotropic network of such elements usually leads to negative values for σ. In fact in two dimensions one can show that $\sigma = (1 - \lambda)/(3 + \lambda)$, with λ as the ratio of the tangential stiffness to the axial stiffness. Whenever $\lambda > 1$, we end up with negative σ. This paper presents results on isotropic networks made up of identical structural units. Three different types of structural units have been discussed in detail to bring home this point that negative σ is a consequence of axial stiffness being much smaller than tangential stiffness.

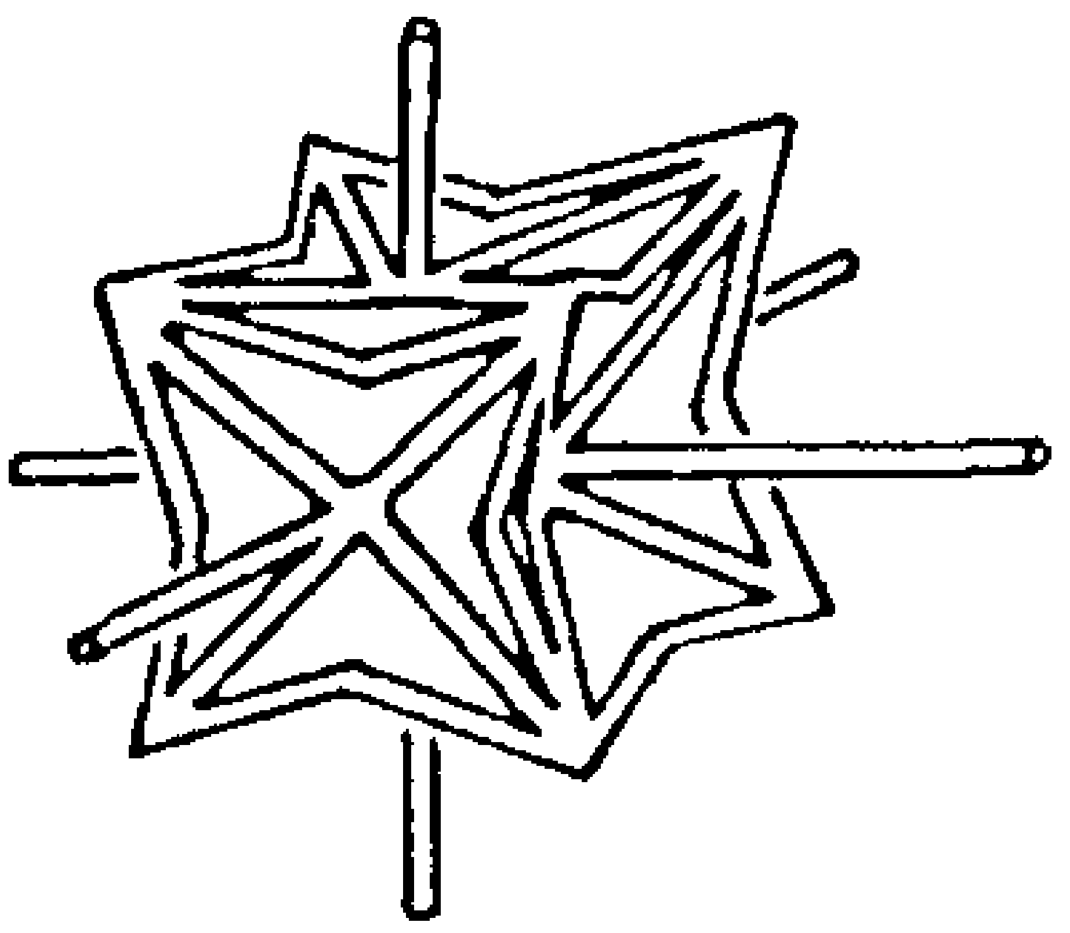

Figure 2. A possible reentrant structure (after Lakes[4])

Shock absorber-like units

Let us say the structural element is very much like a shock absorber, i.e. a spring cushioned piston moving inside a socket (Figure 3*a*). This object can be easily stretched or compressed but it is nearly impossible to shear it. We consider, as an example, an assembly of such units all rigidly fixed to be in the vertical direction. Then under a tensile (or compressive) stress applied along the vertical, we find only axial extension (or compression). There will be no accompanying lateral contraction (or extension). In other words such a network of shock-absorbers has $\sigma = 0$. Rothenburg *et al.* considered an equilateral triangular element (Figure 3*b*) as a structural unit. Under an axial compression, the unit shrinks overall to an equilateral triangular element of smaller size, since the shock absorbers are rigidly fixed at the vertices. This means that we have a lateral contraction under longitudinal compression. Hence the triangular structure has a negative σ. One can build an isotropic network (Figure 3*c*) with such triangles allowing for all possible orientations. These authors showed that such a network will also exhibit a negative σ. The whole network will shrink under an axial compression or swell under an axial extension.

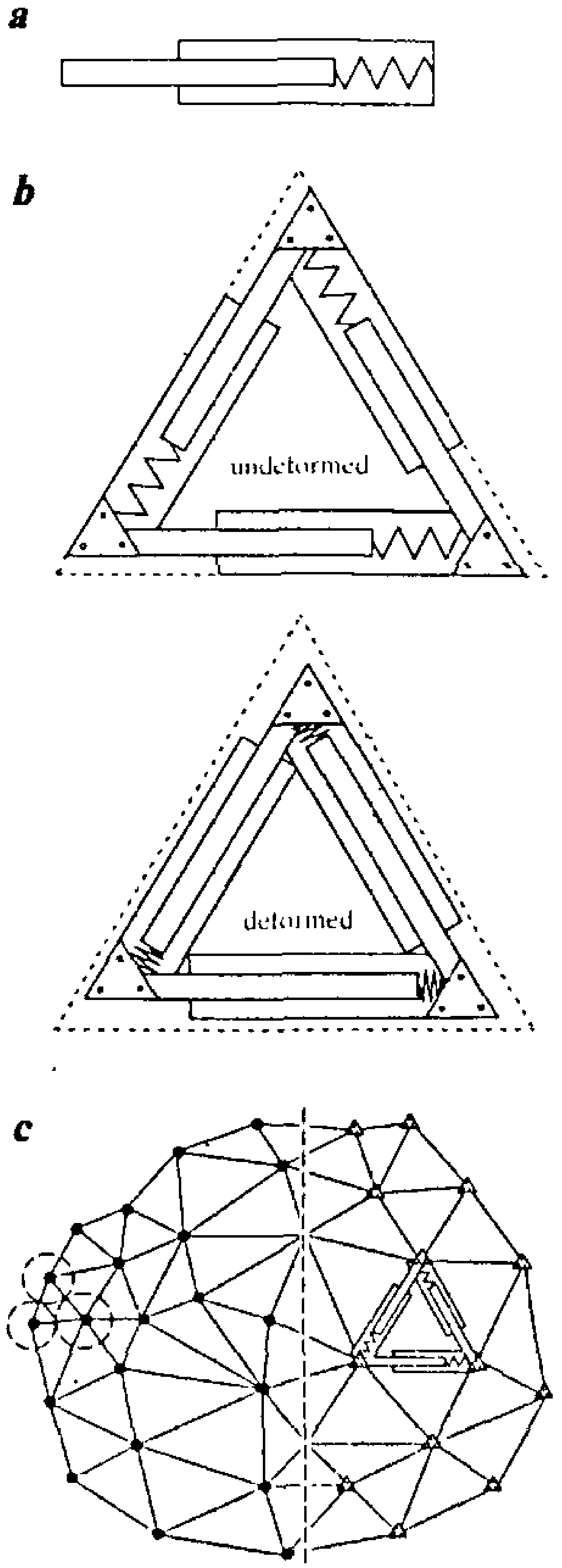

Figure 3. ***a***, A shock-absorber unit, ***b***, a rigid equilateral triangle of shock absorbers, ***c***, an isotropic network of shock absorbers (After Rothenburg *et al*[3])

Kink-like units

The previous example is more in the nature of an engineering structure and is thus not relevant to natural physical systems. A structural unit that is rather realistic in the world of polymers was considered next. It is very easy to see that a rod is difficult to compress or extend axially. But the same rod bent into a kink (as shown in Figure 4*a*) is easy to compress or extend axially along the arms. It has a much reduced axial stiffness. The shear stiffness for both the rod and the kink forms are nearly the same. Hence a network (shown in Figure 4*b*) built out of such kinked elements is likely to have negative σ. Calculations by Rothenberg *et al.* indicate this to be indeed the case. But interestingly this happens only when the compressional ratio (i.e. ratio of the length of the rod to that of the kink) is greater than 1.5. Only then $\lambda > 1$ (Figure 4*a*). For smaller values of the compressional ratio we have positive Poisson's ratio. Hence a network of kinked elements can exhibit negative σ. This example can be looked upon as the two-dimensional analogue of Lakes' compressed foam with reentrant structural units.

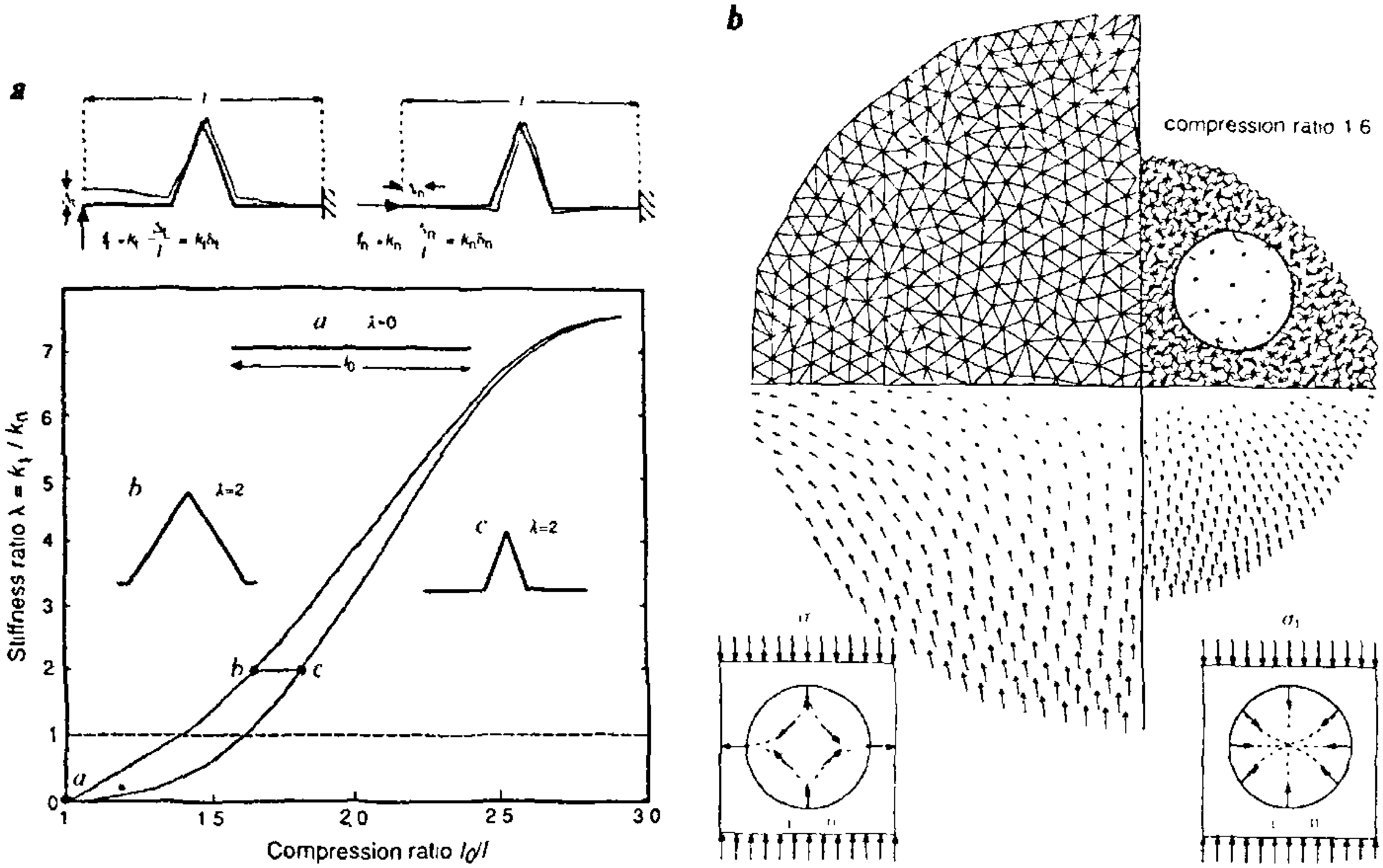

Figure 4. **a**, Compressed bar elements. Insets *a*, *b* and *c* show bar shape corresponding to points *a*, *b* and *c* on the curve. (After Rothenburg *et al*[3]) **b**, Behaviour of an isotropic network of bars (left) and of kinks (right) under a uniaxial compression. Arrows indicate direction of movement of junction points.

Interpenetrating hexagons

The interesting fact that a very low axial stiffness leads to negative σ helps us to appreciate an interesting result of Wojciechowski[5] obtained around the same time. A computer simulation showed that an isotropic 2D solid built out of hexamer molecular clusters (Figure 5) leads to negative σ provided they can penetrate each other. On the other hand, non-penetrating hexamers always leads to positive σ. One can interpret this result in terms of axial stiffness. It is not difficult to convince oneself that in the presence of interpenetration axial stiffness is very much reduced, compared to tangential stiffness which will be nearly the same whether interpenetration exists or not. An extension of this work can easily be imagined in 3D. Interpenetrating spherical molecular clusters can, in principle, lead to negative σ. One is thus at the threshold of

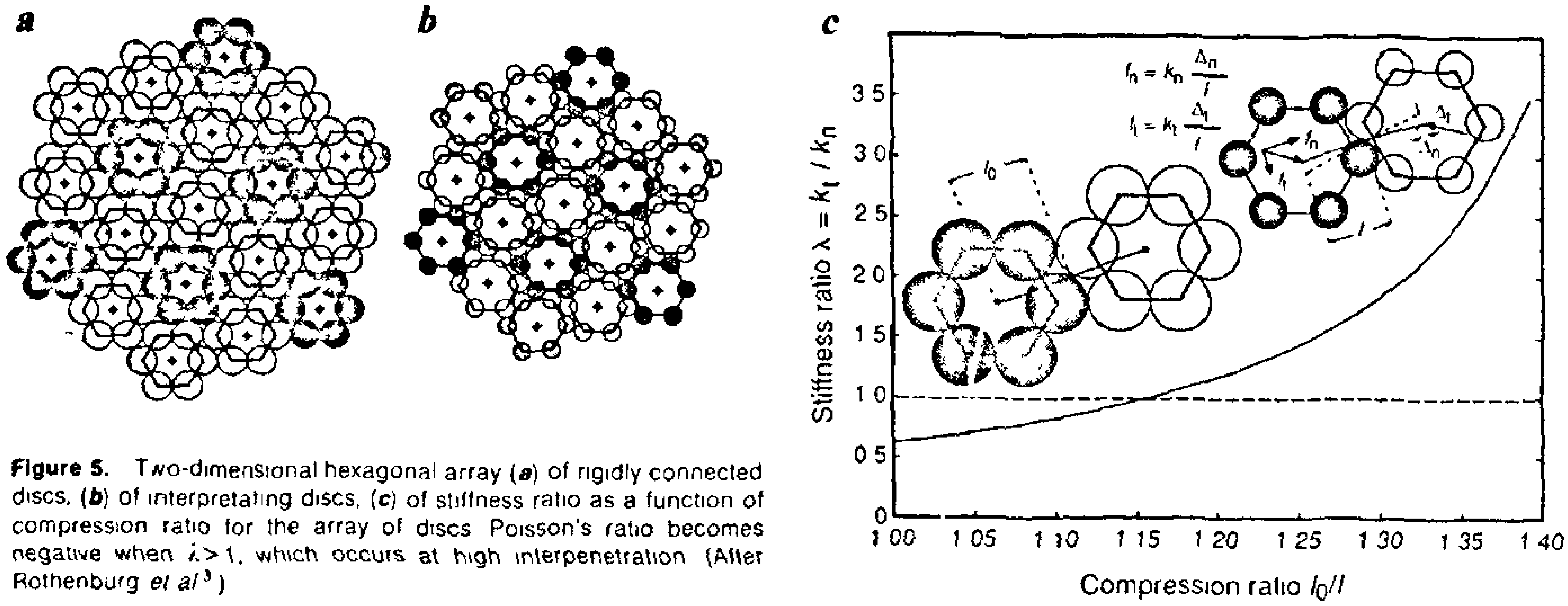

Figure 5. Two-dimensional hexagonal array (**a**) of rigidly connected discs, (**b**) of interpretating discs, (**c**) of stiffness ratio as a function of compression ratio for the array of discs. Poisson's ratio becomes negative when $\lambda > 1$, which occurs at high interpenetration. (After Rothenburg *et al*[3])

almost synthesizing an isotropic solid with negative Poisson's ratio.

Materials with negative σ are expected to have many interesting elastic properties. Since real isotropic materials with negative σ are yet to be synthesized, one can only extrapolate from the results obtained with foams of negative σ. Such materials can be expected to have a large elastic resilence. Normal material are linearly elastic only up to 5% strain. But foams with reentrant units are linear up to 40% strain. These materials are also expected to have large energy absorption and fracture resistance[4]. In the light of these facts we can look forward to a fertile field of study on the elastic properties of solids with negative Poisson's ratio.

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G. S. Ranganath is in the Raman Research Institute, Bangalore 560 012, India

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Trends in experimental neural transplantation

B. K. Misra

Neural transplantation is an exciting and rapidly growing field of research in neurobiology. Last decade has witnessed notable advances in this area. However, the initial hope, that neural transplantation could be a panacea for neurodegenerative diseases, has dwindled due to failure of the implants to survive on a long-term basis and also because the expected functional requirements have not been met. Experimental biologists have responded to these problems through newer approaches and there appears to be no wane in their enthusiasm. The major goals of neural transplantation to the mammalian brain are: (i) to explore the potential of grafts to alleviate symptoms of degenerative diseases, and (ii) to provide an experimental model to study the fundamental biology of the brain. The diverse topics in these areas have recently been reviewed[1].

The concept of transplanting glial cells into mammalian central nervous system to promote regeneration is an extension of the concept of the peripheral nerve-grafting experiments of Cajal and Tello at the turn of the century. Earlier, in 1890, Thompson had already demonstrated that brain grafting is possible[2]. Yet there was a long gap before there was revival of interest in neural transplantation.

Potential of glial cell grafts. The resurgent studies explored the potential of grafts to alleviate symptoms of degenerative diseases. Two important objectives of the glial cell transplantation research are: (i) to understand the interactions of glia, schwann cells and axons during repair in the central nervous system (CNS), and (ii) to explore the theoretical possibility of glial transplantation as a therapeutic means to promote repair of demyelinating plaques in multiple sclerosis and enhance axon regeneration after spinal cord trauma. Significant contribution has been made by Blakemore and Franklin[3] who, in a series of experiments, demonstrated the primary importance of type-1 astrocyte and also the role of cells of the 0–2A lineage, the precursor of oligodendrocyte, in central myelination.

Application of genetically modified cells. A major breakthrough in grafting experiments is the application of genetically modified cells for intracerebral implantation. Two major groups of cells have been successfully used for gene transfer application to the CNS, viz. immortalized cells and primary cells. The advantages of genetically modifed cells are that they can be 'customized' to produce discrete required factors and that, using autologous cells, the host immune responses can be minimized[1].

Genetically modified cells could find therapeutic applications, in genetic disorders like Huntington's chorea, where the disease phenotype can be corrected by introducing functional genes into mutant cells, and in non-genetic disorders of the CNS associated with deficits of specific neurotransmitter systems like Parkinsonism with dopamine depletion. In animal models of Parkinsonism, some of the behavioural abnormalities can be ameliorated with grafts of cells genetically modified to produce L-DOPA or dopamine.

An alternative approach is to deliver neurotropic factors like nerve growth factors (NGF) using genetically modified cells to specific sites like neurones undergoing degeneration. NGF has been shown to protect cholinergic neurones of the basal forebrain and neurones which are affected in Alzheimer's disease from injury-induced degeneration[4].

Transplantation to diseased and damaged retina. The accomplishments in CNS transplantation prompted several workers to explore the possibility of neural transplantation in other sites. The Royal College of Surgeons (RCS) rat, which is one of the most studied animal models for inherited retinal disease, provided the paradigm. In the dystrophic retinas of these rats, photoreceptor cells begin to degenerate during the third postnatal week. The photoreceptor cell layer, normally 8-10 cells thick, is reduced to two cells in thickness, by two months in these rats. Implantation of retinal pigment epithelial cells into the interphotoreceptor space in these retinas, effectively rescues the photoreceptor cells[5]. It has also been shown that a single injection of a high concentration of basic fibroblast growth factor (B