Herbal medicine

V. P. Kamboj

Herbal medicines are the synthesis of therapeutic experiences of generations of practising physicians of indigenous systems of medicine for over hundreds of years while nutraceuticals are nutritionally or medicinally enhanced foods with health benefits of recent origin and marketed in developed countries. The marketing of the former under the category of the latter is unethical. Herbal medicines are also in great demand in the developed world for primary health care because of their efficacy, safety and lesser side effects. They also offer therapeutics for age-related disorders like memory loss, osteoporosis, immune disorders, etc. for which no modern medicine is available. India despite its rich traditional knowledge, heritage of herbal medicines and large biodiversity has a dismal share of the world market due to export of crude extracts and drugs. WHO too has not systematically evaluated traditional medicines despite the fact that it is used for primary health care by about 80% of the world population. However, in 1991 WHO developed guidelines for the assessment of herbal medicine. Suggestions for herbal medicine standardization are outlined. The scenario and perceptions of herbal medicine are discussed.

HERBAL medicine is still the mainstay of about 75–80% of the world population, mainly in the developing countries, for primary health care because of better cultural acceptability, better compatibility with the human body and lesser side effects. However, the last few years have seen a major increase in their use in the developed world. In Germany and France, many herbs and herbal extracts are used as prescription drugs and their sales in the countries of European Union were around \$ 6 billion in 1991 and may be over \$ 20 billion now. In USA, herbal drugs are currently sold in health food stores with a turnover of about \$ 4 billion in 1996 which is anticipated to double by the turn of the century[1]. In India, the herbal drug market is about \$ one billion and the export of plant-based crude drugs is around \$ 80 million[2]. Herbal medicines also find market as nutraceuticals (health foods) whose current market is estimated at about \$ 80–250 billion in USA and also in Europe[3].

India is sitting on a gold mine of well-recorded and well-practiced knowledge of traditional herbal medicine. But, unlike China, India has not been able to capitalize on this herbal wealth by promoting its use in the developed world despite their renewed interest in herbal medicines. This can be achieved by judicious product identification based on diseases found in the developed world for which no medicine or only palliative therapy is available; such herbal medicines will find speedy access into those countries. Backward integration from market demands will pay rich dividends. Strategically, India should enter through those plant-based medicines which are already well accepted in Europe, USA and Japan. Simultaneously, it should identify those herbs (medicinal plants) which are time-tested and dispensed all over in India.

The basic requirements for gaining entry into developed countries include: (i) well-documented traditional use, (ii) single-plant medicines, (iii) medicinal plants free from pesticides, heavy metals, etc., (iv) standardization based on chemical and activity profile, and (v) safety and stability. However, mode of action studies in animals and efficacy in human will also be supportive. Such scientifically generated data will project herbal medicine in a proper perspective and help in sustained global market.

Herbal medicine

The World Health Organization (WHO) has recently defined traditional medicine (including herbal drugs) as comprising therapeutic practices that have been in existence, often for hundreds of years, before the development and spread of modern medicine and are still in use today[4]. Or say, traditional medicine is the synthesis of therapeutic experience of generations of practising physicians of indigenous systems of medicine. The traditional preparations comprise medicinal plants, minerals, organic matter, etc. Herbal drugs constitute only those traditional medicines which primarily use medicinal plant preparations for therapy. The earliest recorded evidence of their use in Indian, Chinese, Egyptian, Greek, Roman and Syrian texts dates back to about 5000 years. The classical Indian texts include *Rigveda*, *Atherveda*, *Charak Samhita* and *Sushruta Samhita*. The herbal medicines/traditional medicaments have, therefore, been derived from rich traditions of ancient civilizations and scientific heritage.

Nutraceuticals

V. P. Kamboj is in the Central Drug Research Institute, Lucknow 226 001, India.
e-mail: root@cscdri.ren.nic.in

This is a term of recent origin (1979) and comprises nutritionally or medicinally enhanced foods with health benefits[3]. These include engineered grain, cereals supplemented with vitamins or minerals or genetically manipulated soybean and canola oil without trans fatty acids, etc. Many pharma and biotech companies have moved into this area since it does not involve regulatory clearances and offers large markets. These companies have extended the term nutraceutical to include pure compounds of natural origin like lovastatin (a lipid lowering agent from red rice yeast), docosahexaenoic acid (a cardiovascular stimulant from algae), sterols, curcumin (from plants), etc. Likewise herbal preparations are being marketed as nutraceuticals or health foods and even the minimum standards laid down by WHO are not followed. It is pertinent to mention that herbal medicines are therapeutics of the indigenous/traditional systems of medicine and it is unethical to classify them as health foods. The regulatory agencies should, therefore, step in to prevent such misuse of natural products/herbal medicines as was done by US-FDA by banning the dietary supplement cholestin (i.e. lovastatin).

Nutraceuticals are in great demand in the developed world particularly USA and Japan. Nutraceutical market in USA alone is about $ 80–250 billion, with a similar market size in Europe and Japanese sales worth $ 1.5 billion[3]. Such huge markets have arisen because of the Dietary Supplement Health Education Act passed by USA in 1994 which permits unprecedented claims to be made about food or the dietary supplement's ability about health benefits including prevention and treatment of diseases. This act has motivated pharma to include not only compounds isolated from fauna and flora but also herbal medicines as nutraceuticals, which is unfortunate. The developing countries also see this as a good opportunity and are marketing such products.

Herbal medicine market

As per available records, the herbal medicine market in 1991 in the countries of the European Union was about $ 6 billion (may be over $ 20 billion now), with Germany accounting for $ 3 billion, France $ 1.6 billion and Italy $ 0.6 billion[3]. Incidentally in Germany and France, herbal extracts are sold as prescription drugs and are covered by national health insurance. In 1996, the US herbal medicine market was about $ 4 billion and with the current growth rate may be more than double by the turn of century. Thus a reasonable guesstimate for current herbal medicine market worldwide may be around $ 30–60 billion. The Indian herbal drug market is about $ one billion and the export of herbal crude extracts is about $ 80 million (Table 1).

The 10 best-selling herbal medicines in developed countries[1] are given in Table 2. The sales of these drugs account for almost 50% of the herbal medicine market. These drugs have been well standardized and some of them namely echinacea, garlic, gingko, ginseng and saw palmeto are supported with mode of action and clinical studies. Amongst the developed countries Germany holds the lead and has published individual monographs on therapeutic benefits of more than 300 herbs. In developing countries, China has compiled/generated data on over 800 medicinal plants and exports large amounts of herbal drugs. India has prepared only a few monographs and its exports are dismal.

Why herbal medicine?

Herbal medicines are being used by about 80% of the world population primarily in the developing countries for primary health care. They have stood the test of time for their safety, efficacy, cultural acceptability and lesser side effects. The chemical constituents present in them are a part of the physiological functions of living flora and hence they are believed to have better compatibility with the human body. Ancient literature also mentions herbal medicines for age-related diseases namely memory loss, osteoporosis, diabetic wounds, immune and liver disorders, etc. for which no modern medicine or only palliative therapy is available. These drugs are made from renewable resources of raw materials by ecofriendly processes and will bring economic prosperity to the masses growing these raw materials.

Herbal medicine scenario in India

The turnover of herbal medicines in India as over-the-counter products, ethical and classical formulations and home remedies of Ayurveda, Unani and Siddha systems of medicine is about $ 1 billion with a meagre export of about $ 80 million. Psyllium seeds and husk, castor oil and opium extract alone account for 60% of the exports. 80% of the exports to developed countries are of crude drugs and not finished formulations leading to low revenue for the country. Thus the export of herbal medicines from India is

Table 1. Market size of herbal medicines

Country	Drug sales in US $ (billion)
Europe (1991)	
Germany	3.0
France	1.6
Italy	0.6
Others	0.8
Europe (1996)	~ 10.0
USA (1996)	4.0
India (1996)	1.0
Other countries (1996)	5.0
All countries (1998)	~ 30.0–60.0

Table 2. Ten best-selling herbal medicines in USA

Drug	Botanical name	Market rank as per sale
Echinacea	*Echinacea* species	1
Garlic	*Allium sativum*	2
Goldenseal	*Hydrastis canadensis*	3
Ginseng	*Panax* species	4
Ginko	*Ginko biloba*	5
Saw palmeto	*Serenoa repens*	6
Aloe gel	*Aloe barbadensis*	7
Ephedra	*Ephedra* species	8
Eleuthero	*Eleutherococcus senticosus*	9
Cranberry	*Vaccinium macrocarpon*	10

Table 3. Frequency of occurrence of medicinal plants in herbal formulations in India

Common name	Botanical name	No. of herbal formulations
Triphala	*Terminalia chebula* *Terminalia belerica* *Emblica officinalis*	219
Yashtimadhu	*Glycyrrhiza glabra*	141
Pipali	*Piper longum*	135
Vasaka	*Adhatoda vasica*	110
Ashwagandha	*Withania somnifera*	109
Mastak (Motha)	*Cyperus rotundus*	102
Gulucha	*Tinospora cordifolia*	88
Daruharidra	*Berberis aristata*	65
Gokshura	*Tribulus terrestris*	65
Kutaja	*Holarrhena antidysenterica*	59
Punarnava	*Boerhavia diffusa*	52

Source: BCIL[2].

negligible despite the fact that the country has a rich traditional knowledge and heritage of herbal medicine. Considering the huge herbal medicine and nutraceutical market in developed countries, India should reconsider exporting crude herbal drugs.

Three of the 10 most widely selling herbal medicines in developed countries, namely preparation of *Allium sativum*, *Aloe barbadensis* and *Panax* species are available in India (Table 2). India is the largest grower of Psyllium (*Plantago ovata*) and Senna (*Cassia senna*) plants and one of the largest growers of Castor (*Ricinus communis*) plant. These are also exported in large amounts and yet our market share is dismal because of export of crude extracts/drugs. Twenty other plants are commonly exported as crude drugs worth $ 8 million. Five of these, namely *Glycyrrhiza glabra*, *Commiphora mukul*, *Plantago ovata*, *Aloe barbadensis* and *Azadirachta indica* are even used in modern medicine. The plants *Glycyrrhiza glabra*, *Piper longum*, *Adhatoda vasica*, *Withania somnifera*, *Cyperus rotundus*, *Tinospora cordifolia*, *Berberis aristata*, *Tribulus terristris*, *Holarrhena antidysenterica* and *Boerhavia diffusa* have been used in 52 to 141 herbal formulations and triphala (*Terminalia chebula*, *Terminalia belerica* and *Embelica officinalis*) alone have been used in 219 formulations (Table 3). In spite of this, efforts have not been made to preserve their germ-plasm from different localities, identification of active plants *vis-à-vis* climatic zone and development of agrotechnologies for their organized farming and use as authentic materials in herbal medicines for better economic gains.

India is one of the 12 mega biodiversity centres having over 45,000 plant species. Its diversity is unmatched due to the presence of 16 different agroclimatic zones, 10 vegetative zones and 15 biotic provinces. The country has 15,000–18,000 flowering plants, 23,000 fungi, 2500 algae, 1600 lichens, 1800 bryophytes and 30 million micro-organisms[5]. India also has equivalent to 3/4 of its land exclusive economic zone in the ocean harbouring a large variety of flora and fauna, many of them with therapeutic properties. About 1500 plants with medicinal uses are mentioned in ancient texts and around 800 plants have been used in traditional medicine; the most widely used plants are given in Table 4. Tables 5 and 6 give the names of medicinal plants exported and imported in India, respectively.

The major traditional sector pharmas, namely Himalaya, Zandu, Dabur, Hamdard, Maharishi, etc. and modern sector pharmas, namely Ranbaxy, Lupin, Allembic, etc. are standardizing their herbal formulations by chromatography techniques like TLC/HPLC finger printing, etc. There are about 7000 firms in the small-scale sector manufacturing traditional medicines with or without standardization. However, none of the pharma has standardized herbal medicines using active compounds as markers linked with confirmation of bioactivity of herbal drugs in experimental animal models.

Table 5. Medicinal plants being exported from India

Botanical name	Part of the plant
Aconitum species (other than heterophyllum)	Root
Acorus calamus	Rhizome
Adhatoda vasica	Whole plant
Berberis aristata	Root
Cassia angustifolia	Leaf and pod
Colchicum luteum	Rhizome and seed
Hedychium spicatum	Rhizome
Heracleum candicans	Rhizome
Inula racemosa	Rhizome
Juglans regia	Bark
Juniperus communis	Fruit
Juniperus macropoda	Fruit
Picrorhiza kurrooa	Root
Plantago ovata	Seed and husk
Podophyllum emodi	Rhizome
Punica granatum	Flower, root and bark
Rauvolfia serpentina	Root
Rheum emodi	Rhizome
Saussurea lappa	Rhizome
Swertia chirayita	Whole plant
Valeriana jatamansi	Rhizome
Zingiber officinale	Rhizome

Source: BCIL[2].

Table 4. Major Indian medicinal plants used in three indigenous systems of medicine

Botanical name	Sanskrit name
Abies webbiana	Taleespatra
Achyranthes aspera	Apamarga
Acorus calamus	Vacha
Aloe sp.	Kumari
Andrographis paniculata	Bhoonimba (Kalmeg)
Asparagus adscendens	Mushali
Asparagus racemosus	Shatavari
Bauhinia variegata	Kachnar
Bergenia ligulata	Pashan bheda
Boerhavia diffusa	Punarnava
Centella asiatica	Mandukparni
Clerodendrum serratum	Bharangi
Convolvulus pluricaulis	Shankhapushpi
Crataeva nurvala	Varuna
Dioscorea bulbifera	Vidarikand
Embelia ribes	Vidanga
Gymnemma sylvestre	Madhunashni
Hedychium spicatum	Shathi
Holarrhena antidysenterica	Kutaja
Mesua ferrea	Nagkesar
Nardostachys jatamansi	Jatamansi
Ocimum sp.	Tulsi
Phyllanthus amarus	Bhumyamalika
Phyllanthus emblica	Amalika (Amla)
Picrorhiza kurrooa	Kutki
Piper longum	Pippali
Pluchea lanceolata	Rasna
Psoralea corylifolia	Bakuchi
Rubia cordifolia	Manjistha
Saraca indica	Ashoka
Saussurea lappa	Kushtha
Sida sp.	Bala
Symplocos racemosa	Lodhra
Terminalia arjuna	Arjuna
Terminalia chebula	Haritaki (Harad)
Tinospora cordifolia	Guduchi
Tribulus terrestris	Gokshura
Valeriana jatamansi	Tagar
Vitex negundo	Nirgundi
Withania somnifera	Ashwagandha

Source: BCIL[2].

Role of WHO in herbal medicine

Two decades ago, WHO referred to traditional health systems (including herbal medicine) as 'holistic' – 'that of viewing man in his totality within a wide ecological spectrum, and of emphasizing the view that ill health or disease is brought about by an imbalance or disequilibrium of man in his total ecological system and not only by the causative agent and pathologenic evolution' (WHO[6]), probably implying that the indigenous system drugs (including herbal medicine) restore the imbalance or disequilibrium leading to the cure of ill health or disease. Such an attitude sent signals that WHO as an organization has failed to provide leadership to establish traditional systems of medicine which provide health care to about 80% of the world population. However, it helped the inclusion of proven traditional remedies in national drug policies and regulatory approvals by developing countries. The World Health Assembly continued the debate and adopted a resolution (WHA 42.43) in 1989 that herbal medicine is of great importance to the health of individuals and communities. The redefined definition of traditional medicine thus issued in the early nineties is given vide supra (see herbal medicine). Consequently, in 1991 WHO developed guidelines for the assessment of herbal medicine[7], and the same were ratified by the 6th International Conference of Drug Regulatory Authorities held at Ottawa in the same year. The salient features of WHO guidelines are: (i) *Quality assessment*: Crude plant material; Plant preparation; Finished product. (ii) *Stability*: Shelf life. (iii) *Safety assessment*: Documentation of safety based on experience or/and; Toxicology studies. (iv) *Assessment of efficacy*: Documented evidence of traditional use or/and; Activity determination (animals, human).

To the best of my knowledge, WHO has not systematically evaluated any traditional medicine.

Herbal medicine standardization

In indigenous/traditional systems of medicine, the drugs are primarily dispensed as water decoction or ethanolic extract. Fresh plant parts, juice or crude powder are a rarity rather than a rule. Thus medicinal plant parts should be authentic and free from harmful materials like pesticides, heavy metals, microbial or radioactive contamination, etc. The medicinal plant is subjected to a single solvent extraction once or repeatedly, or water decoction or as described in ancient texts. The extract should then be checked for indicated biological activity in an experimental animal model(s). The bioactive extract should be standardized on the basis of active principle or major compound(s) along with fingerprints. The next important step is stabilization of the bioactive extract with a minimum shelf-life of over a year. The stabilized bioactive extract should undergo regulatory or limited safety studies

Table 6. Medicinal plants being imported in India

Botanical name	Native name
Cuscuta epithymum	Aftimum vilaiyti
Glycyrrhiza glabra	Mullathi
Lavendula stoechas	Ustukhudus
Operculina turpethum	Turbud
Pimpinella anisum	Anise fruit
Smilax china	Chobchini
Smilax ornata	Ushba
Thymus vulgaris	Hasha

Source: BCIL[2].

in animals. Determination of the probable mode of action will explain the therapeutic profile. The safe and stable herbal extract may be marketed if its therapeutic use is well documented in indigenous systems of medicine, as also viewed by WHO. A limited clinical tribal to establish its therapeutic potential would promote clinical use. The herbal medicines developed in this mode should be dispensed as prescription drugs or even OTC products depending upon disease consideration and under no circumstances as health foods or nutraceuticals.

1. Rawls, R., *C&EN*, Washington, 23 September 1996, pp. 53–60.
2. *Sectoral Study on Indian Medicinal Plants – Status, Perspective and Strategy for Growth*, Biotech Consortium India Ltd, New Delhi, 1996.
3. Brower, V., *Nat. Biotechnol.*, 1998, **16**, 728–731.
4. WHO, in Progress Report by the Director General, Document No. A44/20, 22 March 1991, World Health Organization, Geneva, 1991.
5. *Drugs and Pharmaceuticals – Industry Highlights Incorporating Patent Information*, CDRI, Lucknow, 1998, vol. 21, pp. 33–34.
6. *Traditional Medicine*, World Health Organization, Geneva, 1978.
7. *Guidelines for the Assessment of Herbal Medicines*, Document No. WHO/TRM/91.4, World Health Organization, Geneva, 1991.

ACKNOWLEDGEMENT. I thank EMR (HRDG), CSIR, New Delhi for the grant of Emeritus Scientist Scheme.

Received 30 August 1999; accepted 14 September 1999

The underground flower

Veenu Kaul, A. K. Koul and M. C. Sharma*

There are about 250,000 species of flowering plants in the world. Most of these produce flowers above ground. Thirty six species bear flowers on underground shoots. Flowers produced above ground may be of two types – chasmogamous and cleistogamous. The former are the normal flowers which open to receive pollen and/or pollinators. The latter type do not open and pollination is accomplished when they are closed. Flowers borne on underground shoots are invariably cleistogamous. The chasmogamous flowers are larger in size, produce copious amounts of pollen and large number of small seeds. Contrarily, the cleistogamous flowers are generally reduced in size, produce little pollen and few but heavier seeds[1].

FLOWERING involves transformation of a foliar into a floral bud through a series of histological, physiological and biochemical changes[2–4]. Since flower represents a modified shoot, and shoot is negatively geotropic, flowers almost invariably differentiate above ground. If flowers had been underground, the world would be devoid of the range of colours, variety of scents, and innumerable patterns and forms we see around us. The immense variety and enormous beauty of flowers benefits the plants and appeals the human eye. However, for the plant, underground flower formation could be an asset, as it substantially cuts down resource allocation involved in differentiation of accessory floral parts, biosynthesis of pigments and production of large quantities of pollen and nectar to reward pollinators. Importantly, underground flowers have assured pollination and seed set, with security against predators and vagaries of environment. Nevertheless, the invariable differentiation of flowers above ground has deprived plants of all the above advantages. However, as compensation the above-ground flowers confer on plants the ability for (i) cross-pollination, which generates variability, assures adaptability and evolutionary plasticity, and (ii) wider dispersal of pollen and seed for greater distribution and reducing intrapopulation competition.

That pollination and seed dispersal are the only major events which aerial flowers help to accomplish is reflected by *Tulipa*, *Sternbergia*, *Ixilioron* and such other bulbous angiosperms in which flower development is completed within the bulb, underground. The hidden flower is thrust above ground for accomplishing pollination, whereafter, seeds and fruits develop above ground.

Geocarpy

Have plants ever tried to combine the advantages of above ground flowering and underground development of fruits? The answer is provided by a few plants of which peanut is the most common example. In this legume, flowers diffe-

The authors are at the Department of Botany, University of Jammu, Jammu 180 006, India.

*For correspondence.

rentiate above ground. Soon after pollination, they shed their petals and bend with the help of a peg to first come close to soil surface, and finally become subterranean. Pods and seeds mature underground[5]. This phenomenon of development of fruits underground is called geocarpy.

Besides *Arachis hypogaea*, development of aerial flowers and subterranean fruits is also known in *Trifolium subterraneum*, *Voandzeia subterranea* (L.) Thouars[6] and *Kerstingiella geocarpa* Harms[6].

There are also reports of the differentiation of fertile, cleistogamous flowers on the underground shoots of pea-nut[7–11]. Development of seed from flowers which are *ab initio* underground, is called amphicarpy. However, when these underground buds are brought above the ground and exposed to light, they open readily, and follow normal course of development[5], suggesting that these flowers are not truly cleistogamous and the plants are not truly amphicarpic. Some scientists believe that such flowers differentiate in response to the environment created by farmer's 'plow'[5].

Amphicarpy

During their evolutionary history, differentiation of true underground flowers has been attempted by flowering plants more than once. Of the nearly 250,000 flowering plants, only 36 (Table 1; refs 12–39) are amphicarpic. These are distributed over 10 phylogenetically distantly related

Table 1. List of species that bear cleistogamous flowers on subterranean shoots

Family	Valid name of the species	Reference
Dicotyledons		
Asteraceae	*Catanche lutea* L.	12–15
(Compositae)	*Gymnarrhena micrantha* Desf.	14–17
Brassicaceae	*Cardamine chenopodifolia* Pers.	18, 19; Fig. 1 *a*
(Cruciferae)	*Geococcus pusillus* J. Drumm	14
Fabaceae	*Amphicarpa monoica* (L.) Ell.	18
(Leguminosae)	*Vicia sativa* ssp. *amphicarpa* (Dorth) Aschers & Graebn.	12–15; Fig. 1 *b*
	Vigna minima (Roxb.) Ohwi & Ohashi	20
	Lathyrus ciliolatus Sam. ex. Rech. f.	13–15, 21
	Pisum fulvum Sibth & Sm. var. *amphicarpum* Warb & Eig.	13–15, 22
	Amphicarpaea bracteata (L.) Fern.	23, 24
	Lathyrus amphicarpos L.	
	L. setifolius L. var. *amphicarpos* DC	
	Phaseolus sublobatus Roxb.	cf. 15
	Tephrosia lupinifolia DC Prod.	
	Trifolium polymorphum Poir.	
	Galacita canescens (Scheele) Benth.	
Polygalaceae	*Polygala polygama* Walt.	18
	P. pauciflora	
Polygonaceae	*Emex spinosa* (L) Campd.	15, 25
	Polygonum thunbergii Sieb. et Zucc.	26
Scrophulariaceae	*Scrophularia arguta* Soland.	cf. 15
Urticaceae	*Fleurya podocarpa* var. *amphicarpa* Engl.	cf. 15
Violaceae	*Viola cucculata* Ait., *V. purpurea* Kell., *V. sciaphila**	18
Monocotyledons		
Commelinaceae	*Commelina virginica* L.	18, 27
	C. nudiflora L.	28, 29
	C. indehiscens Barnes.	30
	C. forskalaei Vahl.	18, 31–34; Fig. 1 *c*
	C. benghalensis L.	18, 32, 33, 35; Fig 1 *d*
Poaceae	*Amphicarpum purshii* Kunth	14, 15, 36–39
(Gramineae)	*A. floridanum* Chapman.	36
	A. muhlenbergianum (Schult) Hitchc.	cf. 15
	Chloris chloridea (Presl.) Hitchc.	37
	Eremetis (ca 4 species)	cf. 15
	Paspalum amphicarpum Ekman	36, 37

*Subterranean cleistogamy not confirmed

groups with a maximum concentration in the Fabaceae (~ 10 species) and Poaceae (8 species). Most amphicarpic plants are annuals; only a few are perennial. With a few notable exceptions, the amphicarpic taxa grow well in aerated, well drained sandy or gravely soils.

The characters shared by most amphicarpic plants (see Figure 1 *a–d*) include the presence of (i) self-fertile subterranean flowers that mature into large fruits and seeds with limited dispersal, and (ii) aerial flowers that are capable of cross-pollination and set many smaller fruits and seeds suited to long distance dispersal.

Flowers of aboveground capitula of *Gymnarrhena micrantha* Desf. a dwarf, annual desert composite, are chasmogamous, while those comprising the subterranean capitula are cleistogamous. The aerial capitula bear a large number of small, wind dispersed fruits. On the contrary, the subterranean fruits are large sized and fewer. They are never shed; their seeds germinate *in situ*[16].

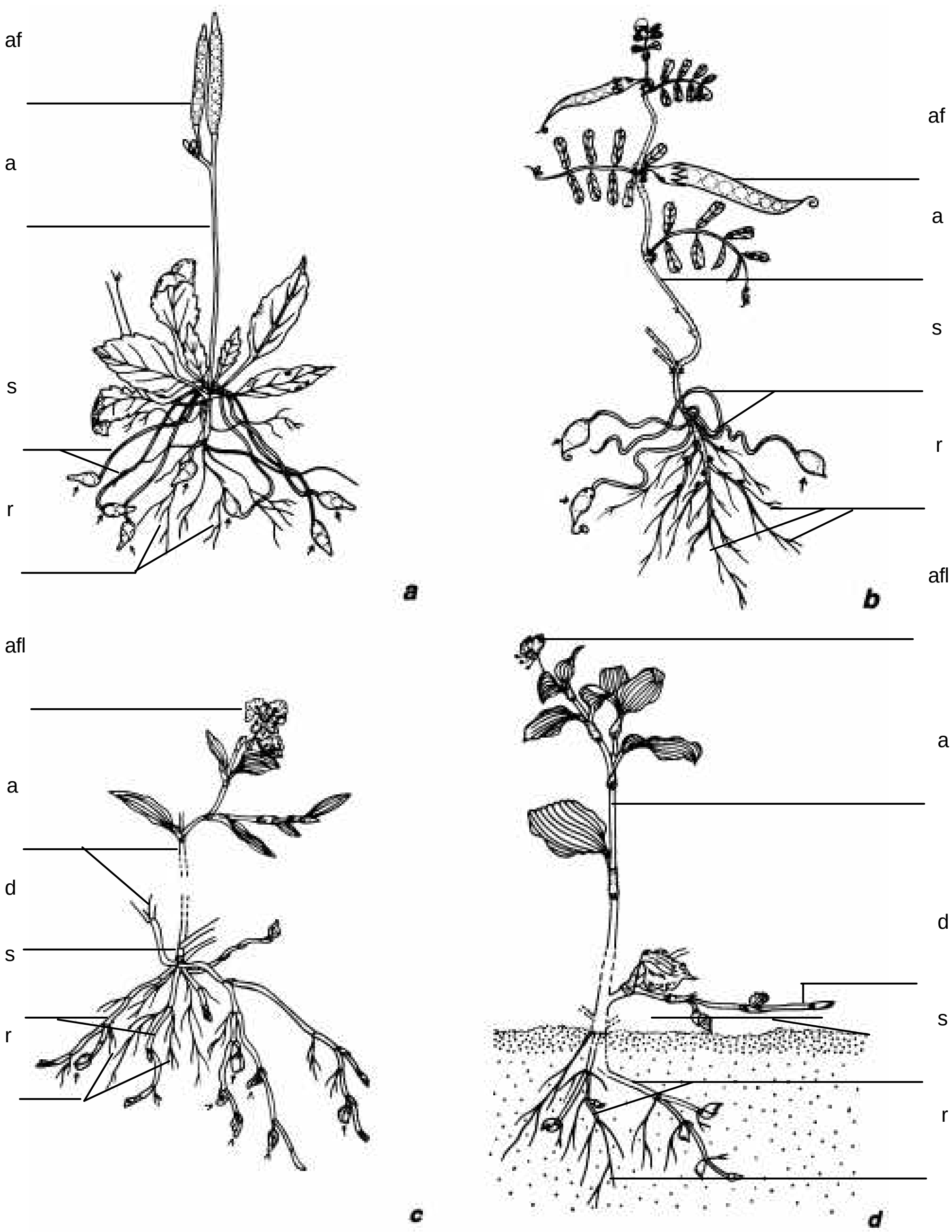

Figure 1 ***a–d***. Hand drawings of plants of (***a***) *Cardamine chenopodifolia*; (***b***) *Vicia sativa amphicarpa*; (***c***) *Commelina forskalaei*; and (***d***) *C. benghalensis* showing fruits/flowers (marked by arrows) on aerial and underground shoots. r, roots; a, aerial; s, subterranean and d, diageotropic shoots; af, fruits; afl, flowers on aerial shoots.

Aerial flowers of the plant are potentially open-pollinated, which helps in increasing the genetic variability of the population. The wind dispersed achenes widen the distribution of the species to distant habitats. Subterranean flowers are invariably self-pollinated and are therefore, instrumental in preserving the parental genotype. Underground fruits and seeds improve chances of survival of these plants at specific microhabitats.

Amphicarpum purshii Kunth., an annual panicoid grass, also bears aboveground and subterranean spikelets on the same individual. The former are small and chasmogamous, while the latter are large and cleistogamous. The subterranean seeds are few but heavy. These account for most progeny seedlings. Aerial florets outnumber the subterranean flowers and contribute to the widening of genetic variability of the species[38].

Relative cost of aerial and underground flowers as exemplified by *Commelina* sp.

In the genus *Commelina* of Commelinaceae, five species are known to produce underground cleistogamous flowers. *Commelina forskalaei* (Figure 1 *c*) and *C. benghalensis* (Figure 1 *d*) bear flowers on three types of shoots[33,34]; positively geotropic subterranean shoots, negatively geo-

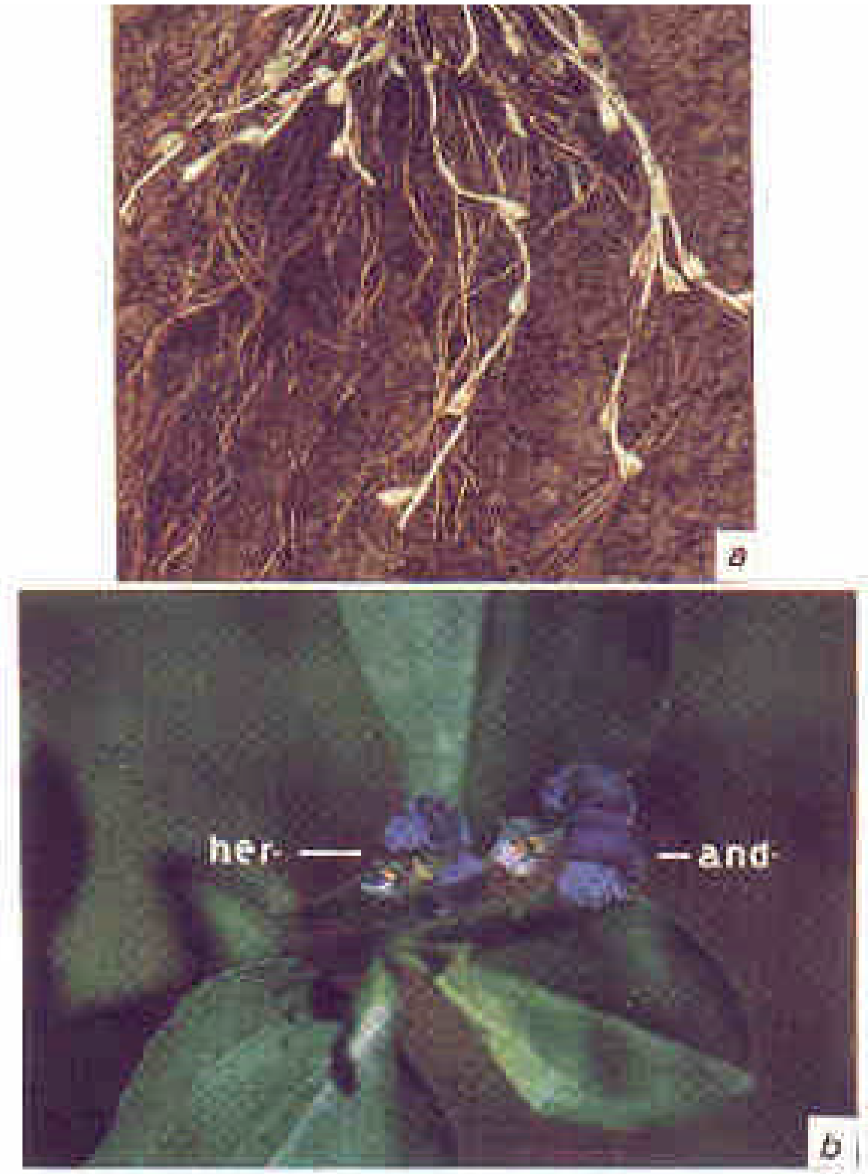

Figure 2. ***a***, An uprooted plant of *C. benghalensis* with exposed roots (brown) and underground shoots (white) laden with flower containing spathes (white). ***b***, Male (androgenic; and.) and hermaphrodite (her.) flowers of an aerial spathe of *C. benghalensis* in bloom (× 3).

tropic cauline shoots and diageotropic shoots which run parallel to soil surface. The positively geotropic leafless shoots grow deep into the soil, and carry flowers inside colourless spathes (Figure 2 *a*). Flowers on other two types of shoot differentiate in green spathes and vary in number as well as structure. In *C. benghalensis* spathes on the diageotropic and subterranean shoots have a single hermaphrodite flower each, but aerial spathes have three and occasionally four flowers each. Flowers of aerial spathes are trimorphic; the oldest is male and chasmogamous, the second is hermaphrodite and chasmogamous and the youngest is hermaphrodite and cleistogamous (Figure 2 *b*). Flowers of the diageotropic spathes are always chasmogamous, and those of the subterranean spathes are invariably cleistogamous.

The subterranean cleistogamous flowers are obligately self-pollinated. Their floral parts are small. The ratio between the resources consumed in the differentiation of their essential (stamens and carpels) and accessory organs (sepals and petals) is 3 : 2 (60 : 40%). Resource expenditure on pistil differentiation is 20% higher than that on the differentiation of stamens. This is reflected in the greater biomass of the pistil. Cleistogamous flowers have fewer pollen grains and their pollen–ovule ratio is 2,305 : 1. They also produce fewer but larger and heavier seeds than their counterparts on aerial and diageotropic shoots. This increase in size and weight of seeds is caused by the diversion of resources saved from male function and differentiation of extrafloral parts to the female function. The diversion is made possible by assured pollination due to cleistogamy despite the availability of fewer ovules borne by the pistil.

On the contrary in all chasmogamous flowers, aerial as well as diageotropic, greater share of resources is invested in floral advertisement; it approaches 62% in male and 42–50% in hermaphrodite chasmogamous flowers. From the total reproductive investment on chasmogamous hermaphrodite flowers, 56–61% investment is channelized to male function. Even in cleistogamous flowers of the aerial branches, the ratio between pistil and stamen biomass is male biased unlike their subterranean counterparts.

Although anther dehiscence and stigma receptivity overlap in hermaphrodite chasmogamous flowers leading to self-pollination, these flowers hold the potential for cross-pollination because of their colourful petals and anthers, profuse pollen production and very frequent visitation by a variety of hymenopteran insects. The potential for cross-pollination can get expressed in the event of the failure of self-pollination.

From what has been stated above, it follows that reproduction through underground flowers is less expensive, yet more assured. In terms of investment/allocation of the resources, the seed produced underground is cheaper than that set above-ground. If selection pressure has not worked against above ground flowers, and they continue to differentiate on the plant, it is because they help in retrieving one of the costs of sex, that of sharing gene(s)[40] through occasional outcrossing.

In most amphicarpic plants including *C. benghalensis*, seedlings produced by subterranean seeds are more vigorous than those produced by aerial seeds. As a consequence, they have greater competitive ability and better survival compared to seedlings resulting from aerial flowers/fruits.

According to Cheplick and Quinn[14], it is perhaps on account of the importance of subterranean seeds to individual fitness that they are produced early in ontogeny, well in advance of aerial seeds. Zeide[17] has termed early production of subterranean seeds and fruits a ‘pessimistic’ strategy of plants, suited to highly disturbed habitats, where survival even up to the end of growing season is uncertain. In such situations it is a definite advantage if plants produce fruits as early as possible. In contrast, the formation of aerial fruits is an ‘optimistic’ strategy, whereby reproduction is delayed until the end of growing season, when time and growth conditions have resulted in accumulation of sufficient resources in the plant body[15].

Evolution of amphicarpy

What factors have led to the evolution of amphicarpy is a question that remains to be answered. A number of hypotheses have been proposed from time to time. Since subterranean seed production has evolved independently in phylogenetically unrelated taxa, the factors underlying their evolution are most likely to differ from species to species. Mattatia[13,21] believes that amphicarpy in the genus *Lathyrus* has arisen independently at least three times.

According to one hypothesis, the adaptive significance of subterranean seeds is to expose them and the plants differentiating therefrom to similar, presumably favourable, microhabitat as that of the parent. However, in experiments conducted on *Amphicarpum purshii*, plants raised from subterranean seeds close to the parent did not always outperform the plants raised at places far removed from the parent[15]. A related possibility is that being better shielded from the extreme fluctuations of microclimate at the soil surface, the buried seeds retain viability, germinate and establish seedlings far better than the seeds lying exposed on soil surface. This hypothesis seems particularly plausible for those amphicarpic plants which inhabit dry habitats since ‘active seed burial will, for instance, ensure availability of greater soil moisture’[15]. Supporting evidence for this comes from *Emex spinosa*[25], *Amphicarpum purshii*[15] and to a certain extent *Commelina benghalensis*. In all these taxa, none (some in *C. benghalensis*) of the subterranean seeds germinated when they were spread on the soil surface. However, this hypothesis does not explain evolution of subterranean seed production in species inhabiting mesic environments.

Another hypothesis is that severe predator pressure must have led to the evolution of subterranean seed production which is understandable since buried flowers, fruits and seeds are comparatively safe from foraging animals. 'In grasses, it is easy to envisage the selective advantage of subterranean seed production under conditions of intense grazing[15].' Even in deserts where animals can be a major cause of seed predation, seed burial might be an adaptive response.

Detailed comparative data on the effect of herbivory on aerial and subterranean flowers, fruits and seeds are required to confirm this hypothesis.

Another advantage which can accrue to a plant from subterranean seeds becomes explicit during a major disturbance which periodically destroys the aerial portion of a herbaceous plant. At this critical juncture in plant's life cycle, only individuals producing subterranean propagules would contribute to the formation of next generation. This would be true especially for annuals which usually lack vegetative propagation and therefore, have a single means of reproduction. In *Amphicarpum purshii*[15], *Vigna minima*[20] and *Commelina virginica*[27], amphicarpy has been viewed as possible adaptation to escape fire.

All the above hypotheses concede selective advantage to subterranean reproduction. If this were so, why do amphicarpic plants still produce aerial seeds? Is it for combating the constraints associated with subterranean reproduction? The retention of aerial flowers may be a selective compromise between the risks associated with production of either of the two types of flowers.

Detailed ecological, evolutionary and physiological studies are required to fully appreciate the actual significance of underground flowers.

1. Lord, E., *Bot. Rev.*, 1981, **47**, 421– 450.
2. Esau, K., *Plant Anatomy*, Wiley Eastern, New Delhi, 1974, 2nd edn.
3. Cutter, E. G., *Plant Anatomy – Part 2: Organs*, Edward Arnold, 1978.
4. Fahn, A., *Plant Anatomy*, Pergamon Press, Oxford, 1989, 3rd edn.
5. Smith, B. W., *Am. J. Bot.*, 1950, **37**, 802–815.
6. *Tropical Legumes: Resources for the Future*, National Academy of Sciences, Washington, DC, 1981, pp. 47– 53.
7. Meisnes, C. F., *Lipsiae*, 1836–1843, p. 97.
8. Kurtz, F., *Sitz*, 1875, **22**, 42–56.
9. Richter, C. G., *Inaug. Diss kgt bot Gart Breslau A Schreiber Breslau*, 1899, p. 39.
10. Theune, E., *Biol Pflanzen F Cohn*, 1916, **13**, 285–346.
11. Bouffil, F., *Sect. techd' Agric. Tropicale Bull. Sci.*, 1947, **1**, 1–112.
12. Plitmann, U., *Isr. J. Bot.*, 1973, **22**, 178–194.
13. Mattatia, J., Ph D thesis, Hebrew University, Israel, 1976.
14. Cheplick, G. P. and Quinn, J, A., *Oecology*, 1982, **52**, 327–332.
15. Cheplick, G. P. and Quinn, J, A., *Tree*, 1987, **2**, 97–101.
16. Koller, D. and Roth, N., *Am J. Bot.*, 1964, **51**, 26–35.
17. Zeide, B., *Am. Nat.*, 1978, **112**, 636–639.
18. Uphof, J. C. Th., *Bot Rev.*, 1938, **4**, 21–49.
19. Cheplick, G. P. and Quinn, J.A., *Oecology*, 1983, **57**, 374–379.
20. Gopinathan, M. C. and Babu, C. R., *Pl. Syst. Evol.*, 1987, **156**, 117–126.
21. Mattatia, J., *Bot. Notiser*, 1977, **129**, 437–444.
22. Mattatia, J., *Bot Notiser*, 1977, **130**, 27–34.
23. Trapp. E. J., *Am. J. Bot.*, 1988, **75**, 1535–1539.
24. Trapp. E. J. and Hendrix, S. D., *Oecology*, 1988, **75**, 285–290.
25. Weiss, P. W., *Oecology*, 1980, **45**, 244–251.
26. Kawano, S., Hara, T., Hiratsuka, A., Matsuo, K. and Hirota, I., *Plant Species Biol.*, 1990, **5**, 97–120.
27. Mendes, C. V. J., Beltrait, C. M. and Paoli, A. A. S., *Rev. Bras. Biol.*, 1994, **54**, 403–412.
28. Calvino, E., *Mem. Soc. Cubana Hist. Nat.*, 1922, **4**, 45–77.
29. Calvino, E., *Mem. Soc. Cubana Hist. Nat.*, 1923, **5**, 99–105.
30. Barnes, E., *J. Bom. Nat. Hist. Soc.*, 1949, **46**, 70–89.
31. Hagerup, O., *Dansk. Bot. Ark.*, 1932, **8**, 1–20.
32. Trochain, J., *Acad. Sci. Colon.*, 1932, **194**, 743–745.
33. Maheshwari, P. and Maheshwari, J. K., *Phytomorphology*, 1955, **5**, 413–422.
34. Maheshwari, S. C. and Singh, B., *Phytomorphology*, 1958, **8**, 277–298.
35. Maheshwari, P. and Singh, B., *Curr. Sci.*, 1934, **3**, 158–160.
36. Weatherwax, P., *Bull. Torrey Bot. Club*, 1934, **61**, 211–215.
37. Connor, H. E., *N. Z. J. Bot.*, 1979, **17**, 547–574.
38. Mc Namara, J. and Quinn, J. A., *Am. J. Bot.*, 1977, **64**, 17–23.
39. Cheplick, G. P. and Quinn, J. A., *J. Ecol.*, 1988, **76**, 263–273.
40. Schoen, D. J., *Oecology*, 1982, **53**, 255–257.

ACKNOWLEDGEMENTS. V.K. thanks the Head, Department of Botany, University of Jammu for providing the necessary library and laboratory facilities and to Council of Scientific and Industrial Research, New Delhi, for the award of Junior and Senior Research Fellowships.

Received 15 June 1999; revised accepted 28 October 1999

The Chamoli earthquake, Garhwal Himalaya: Field observations and implications for seismic hazard

Kusala Rajendran, C. P. Rajendran, Sudhir K. Jain, C. V. R. Murty and Jaswant N. Arlekar*

The Chamoli earthquake in the northern part of Uttar Pradesh is an important event from the point of view of seismic hazard and risk assessment in the Himalaya. Tectonically, it is significant due to its location in the 'central seismic gap', a 700-km-long segment between the 1905 Kangra (M 8.6) and the 1934 Bihar (M 8.4) earthquakes. Occurrence of two moderate earthquakes (1991 Uttarkashi and 1999 Chamoli) within a period of nine years naturally raises concern about the seismogenic potential of the region. In this paper we present observations made during the post-earthquake survey around Chamoli, and address some issues regarding the regional seismic hazard.

THE Chamoli earthquake of 29 March 1999 is yet another moderate event of this decade in the Garhwal Himalaya. It occurred at 00:35:13.59 h (local time) near the town of Chamoli in northern India (Figure 1 *a* and *b*). The US Geological Survey (USGS) located the event at 30°49.2′N, 79°28.8′E (m_b 6.3 and M_s 6.6), and the India Meteorological Department (IMD) located it at 30°17.82′N, 79°33.84′E (m_b 6.8 and M_s 6.5; focal depth ~ 15 km). A long aftershock sequence including at least three events of $M > 5$ followed the main event, some of which were located using local and regional stations (Figure 2 *a*). The USGS fault-plane solution indicates a pure thrust mechanism with two nodal planes striking at 282° and 97° (Figure 2 *b*).

The earthquake triggered landslides, blocked several roads, and disturbed electricity and water supply. A maximum intensity of VIII (MSK) has been attributed to this event[1]. Maximum damages occurred in the district of Chamoli where nearly 2600 houses collapsed and over 10,800 were partially damaged, leaving about 100 dead and 400 injured. The quake was also felt at far-off places such as in Kanpur (440 km south-east), Shimla (220 km north-west) and Delhi (280 km south-west). A few buildings in Delhi sustained non-structural damages[1].

The Chamoli event is important from various considerations. One: its location in the 'central seismic gap' (Figure 1 *a*), a segment of the Himalaya that is considered to have the maximum potential for a large earthquake[2,3]. Two: its proximity to the high dam under construction near Tehri, ~ 125 km west of Chamoli. Here, we present some of the observations made in the Chamoli area and discuss the significance of this earthquake in our understanding of the seismic hazard of the region.

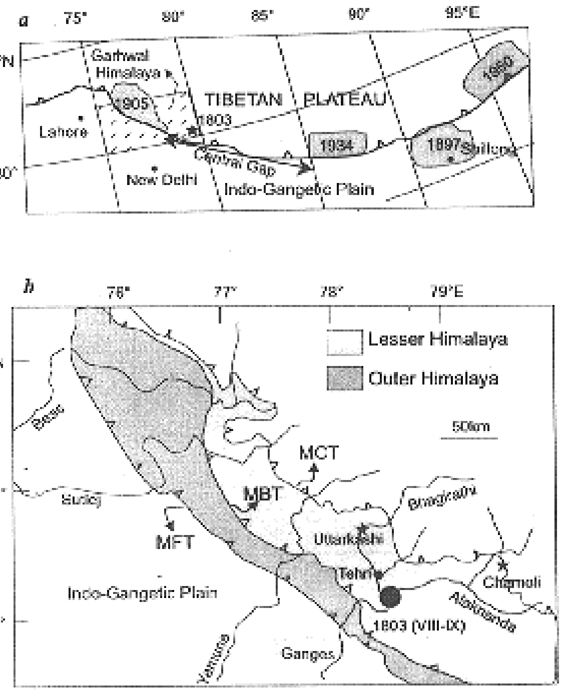

Figure 1. ***a***. Sketch map of the Himalaya[11] showing the Himalayan front (solid line). Meizoseismal area of four great earthquakes are shaded in grey. Hatched area is enlarged in Figure 1 *b*; ***b***. Simplified geologic map of the north-western India[4]. Locations of the Uttarkashi and Chamoli earthquakes are shown. The region where maximum intensity was observed[18] during the 1803 earthquake is indicated by solid circle. Location of Tehri dam is also shown.

Kusala Rajendran and C. P. Rajendran are in the Centre for Earth Science Studies, P.B. No. 7250, Akkulam, Thiruvananthapuram 695 031, India; Sudhir K. Jain, C. V. R. Murty and Jaswant N. Arlekar are in the Department of Civil Engineering, Indian Institute of Technology, Kanpur 208 016, India.

*For correspondence. (e-mail: kusala@vsnl.com)

Geologic and tectonic setting

The Himalayan mountain range, an outcome of the compressional processes ensued by the India–Asia collision (70–40 Ma) has been undergoing extensive crustal shortening along the entire 2400-km-long northern edge of the Indian plate. A series of major thrust planes – the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) – have been formed as a result of these processes[4,5]. In some models, these thrust faults are considered to have evolved progressively, leaving the older ones dormant whereas in others, they are treated as contemporaneous. For example, the evolutionary model[6,7] considers the MCT to be an older thrust plane that was more active in the early phases of the Himalayan orogeny and MBT as a younger one that is more active currently. The steady-state model on the other hand, treats the MCT and the MBT to be contemporaneous and merging at depths with a common detachment surface where the great Himalayan earthquakes are believed to originate[8].

The seismicity of the Himalaya, therefore, needs to be understood in terms of the relative roles of these faults. It has been argued on the basis of focal mechanisms[9] that the MCT is probably aseismic and the current activity is on the MBT. However, Chander[10] noted that the coseismic ground elevation changes observed during the 1905 Kangra earthquake could not be explained by assuming slip on the MBT. The pronounced band of seismicity observed beneath and south of MCT in Kumaun and Nepal[11,12] is another indication of active deformation. The earthquakes recorded during 1984–1986 by a network of stations in the Yamuna and Bhagirathi valleys are also noted to be following a trend of the MCT[13]. The 1991 Uttarkashi earthquake (Figure 1 *b*) is the most recent activity associated with the MCT[14].

Tectonically, the MCT represents a ductile shear zone at depth, comprising a duplex zone with three distinct thrust planes: MCT I, MCT II and MCT III from south to north. Based on the degree of metamorphism, lithostratigraphy and tectonic setting, these thrust planes are also referred to as *Chail* (MCT I, lower thrust), *Jutogh* (MCT II, middle thrust) and *Vaikrita* (MCT III, upper thrust)[15]. Of these, the Chail Thrust (MCT I), the southern-most and the youngest, is believed to have moved during the Uttarkashi earthquake[14]. The Chamoli earthquake appears to be associated with the ongoing deformation along this thrust.

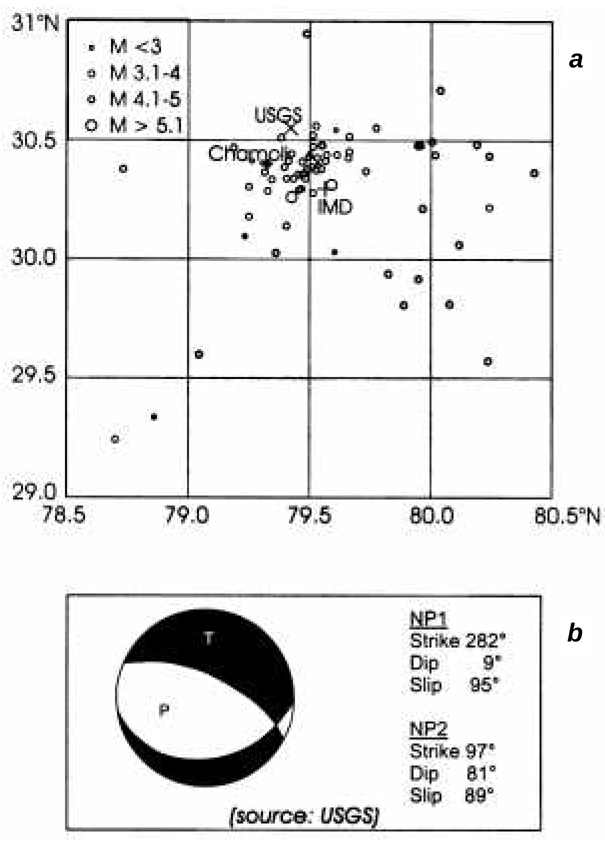

Figure 2. ***a***. Aftershocks until 8 April, as reported by IMD. Main shock locations by IMD and USGS are also indicated; ***b***. Fault plane solution of the main shock (Source: USGS).

An active fold?

The Lesser Himalayan sequence lying between the MCT and the MBT shows stacking of various groups of rocks characterized by south-vergent imbricate thrusts, which were later folded into major scale synforms and antiforms[15]. Geological map of the area indicates presence of an anticlinal structure very close to Chamoli[15]. The whole area, considered as a schuppen zone, is delimited on two sides by almost vertical faults – the E–W trending Alaknanda fault in the south and the NNW–SSE trending Nandaprayag fault in the east[15]. Several parallel faults have been mapped within this schuppen zone and one interpretation is that, these faults demarcate isoclinal anticlines split along the contacts of various litho-units[15].

During the post-earthquake investigations, we observed some signatures of recent deformation, associated with the anticline mapped near Chamoli. A sharp contact of MCT I with recent/sub-recent deposits was located on the southern flanks of this anticline. Thick deposit of colluvium (boulders and pebbles intercalated with coarse sand) occurs at the foot of the steeper limb of the fold (Figure 3). The colluvium may have been remobilized on an incipient slope due to the development of the growing fold. Such surficial features have been associated with fault propagation folds[16]. We interpret the contact near Chamoli to be the surface expression of an active fold. The tight compressional folding in the Berinag quartzite and the stretching lineation in mylonitic quartzite observed at these localities are suggestive of the intense shortening along this contact.

The above observations are significant because the contact of the thrust plane occurs very close to the epicentral zone of the Chamoli earthquake. Although the models for many earthquakes including the Uttarkashi event suggest the rupture along MCT I[14], geological evidences for active faulting in this region are sparse. From this point, the above observations from the epicentral region of the Chamoli earthquake may provide certain clues to identify active faults/folds in the Himalaya. The present data by themselves are insufficient to suggest the nature of the ongoing deformation in this region, but they provide pointers for selecting sites for palaeoseismological and related investigations.

Historic and current seismicity

Although four great earthquakes ($M > 8$) have occurred along the Himalayan front during the last 100 years, the Garhwal region is not known to have experienced a magnitude 8 or larger earthquake in the recorded history[13]. Historic and recent seismicity of the Kumaun–Garhwal region (Figure 4) suggests the occurrence of at least three earthquakes of $M > 7$ in this region. The largest historic earthquake reported from this region occurred on 1 September 1803 (ref. 17). Several villages were reported to have been buried by rockfalls and landslides caused by this earthquake[18]. The Badrinath temple located ~ 40 km north of Chamoli was severely damaged in this earthquake. The epicentre based on the maximum intensities is located ~ 100 km west of Chamoli[18].

We examined two temples (7th–12th century AD) at Gopeshwar and Makkumath, both of which have been reconstructed at least once in the past. Inscriptions on stones, supported by historic data testify that the damages to these temples caused by the 1803 event were substantial and that the smaller structures around the main shrine were totally destroyed. It should be noted that the temples at Gopeshwar and Makkumath suffered only minor vertical cracks during the 1999 earthquake, in spite of their locations in the meizoseismal area, possibly because the 1803 event was much larger. Based on the extent of affected areas, it has been suggested that the 1803 event is a much larger earthquake on the detachment surface[8].

Figure 3. Contact zone of the Berinag quartzite (north-eastern side) and the colluvium of pebbly sediments (south-western side) developed on a growing anticlinal fold. This section is exposed on the banks of the Alaknanda river near the Chamoli town. Whitish rock (Berinag quartzite) in the foreground forms part of the uplifted terrace (~ 1.5 m from the present river bed).

Intensity of shaking, site effects and coseismic processes

The area affected by the Chamoli earthquake lies in seismic zone V (IS:1893–1984), implying a potential for shaking intensity of IX (and above) on the Modified Mercalli scale. Our survey indicates that the maximum intensity of the 1999 event was only VIII (Figure 5). Intensity showed rather abrupt changes from one location to another, probably due to the local site conditions. For instance, the intensity of shaking at Upper Birahi located on the river terrace was VIII, whereas it was only VI at Lower Birahi located on the hard rock (Figure 5). Similarly, Lower and Upper Chamoli showed intensity VIII whereas Gopeshwar, located 2 km away on the

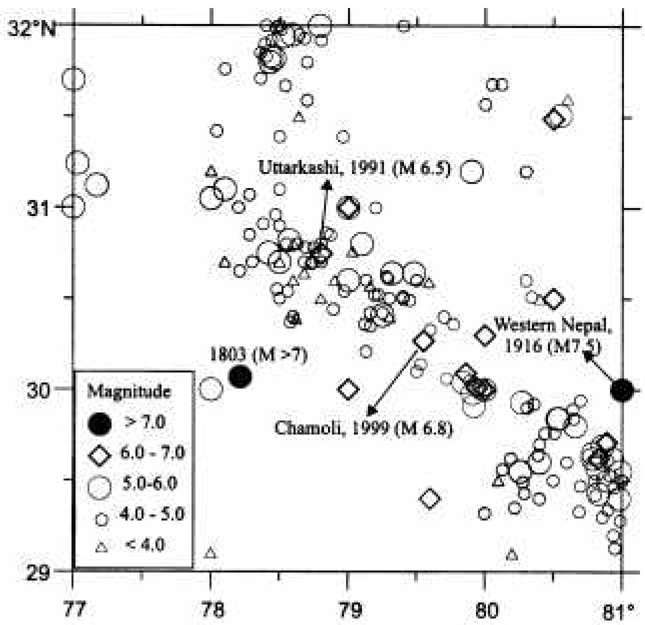

Figure 4. Historic and recent seismicity data (1803–1988) in the Kumaun and Garhwal regions (Source: IMD, 1988).

hill slope, showed intensity V. Higher intensity observed at Makkumath, located on the river terrace, ~ 15 km north-west of Chamoli, is another example of site amplification.

Ground cracks developed at several places as part of slope failure, causing threat to the settlements. Well-developed ground cracks trending roughly in the east–west direction and showing lateral movement of up to ~ 12 cm were observed at Gopeshwar, Chamoli and Bairagna (Figure 6). Attempts to make trenches across the ground fissures at Telecom Hill in Gopeshwar were unsuccessful since these were bottomed on the rubble and boulders at shallow depths (~ 1 m), which form a part of the debris. In one of these trenches, a poorly defined thrust plane was detected, but its growth and overburden followed a complex pattern. Although the trench sections did not reveal fault planes convincingly, the fissures which had cut through concrete steps and well-consolidated debris could be traced for nearly 1 km. Orientation of these ground fissures, although discontinuous, conforms to the trend of the MCT and also to one of the nodal planes (282°) inferred from the focal mechanism (Figures 2 and 4). The predominance of east–west oriented fissures, particularly those developed in the well-consolidated debris, may be manifestation of a blind thrust.

The earthquake was also associated with marked changes in groundwater discharge. In many groundwater springs, flow increased by as much as ten times, surpassing even the post-monsoon discharge. Flow decreased and the water turned muddy, in one spring near village Bairagna, a possible indication of fluidization and remobilization of fine sediments.

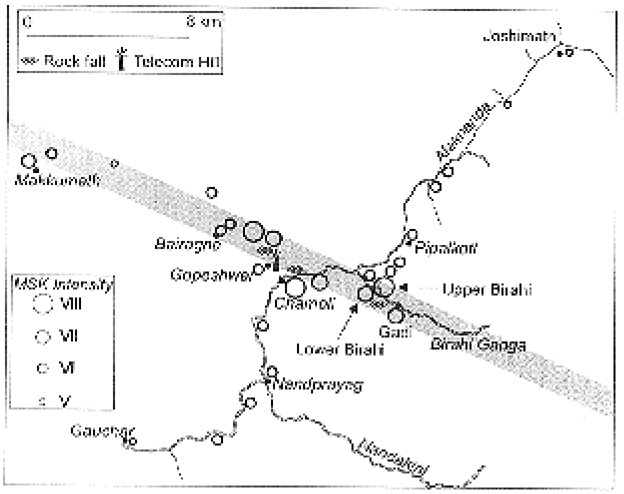

Figure 5. Intensity of shaking observed at various locations around Chamoli. Shaded portion shows the trend of the fault as per the fault plane solution which is consistent with the damage distribution.

Response of structures

The building stock in the affected area consists primarily of rural dwellings, urban houses and a few modern constructions. Load-bearing random rubble stone masonry in mud mortar forms the predominant wall system. Brick or concrete block masonry in cement mortar is used in many newer constructions. The roofing system is usually thatch, tin sheets, slate tiles, or reinforced concrete (RC) slabs. Many recent constructions are in RC frames, with masonry infill walls. In general, most of these are non-engineered with no formal involvement of engineers in design or construction. In this session we briefly discuss the performance of common types of buildings in these areas.

Traditional stone dwellings

The traditional dwellings in the area are usually made up of one or two storeys with a rather low storey height (~ 1.65 m). The walls are about 0.45–0.60 m thick and are made of random rubbles or slate wafers. The former type of walls has two separate layers, the outer and inner wythes, the intervening space being filled with stone rubble. In the latter type, dressed stones and slate wafers are stacked tightly using very little or no mud mortar. Most dwellings have wood rafter roof supported directly on the walls. Many old constructions and a few new buildings have wood rafter roof supported on vertical wooden posts. Some

Figure 6. Ground fissure at Telecom Hill near Gopeshwar.

of the new constructions use RC roof directly resting on the walls.

Houses described above performed poorly, as expected, and most deaths and injuries were caused by the collapse of such constructions. Among these types of constructions, those with masonry walls in slate wafers performed better than those in random rubble masonry, probably due to better interlocking in the latter. The most common damage pattern was the separation of wythes following which the walls tended to buckle (Figure 7).

Brick masonry buildings and buildings with lintel bands

In general, buildings with burnt brick masonry in mud or cement mortar performed much better than the traditional stone masonry buildings. Numerous recent constructions in stone as well as brick/concrete block masonry are provided with a RC lintel band. Often rooms are provided with a RC shelf of about half metre width, projecting from the wall at the lintel level, serving the dual purpose of a storage slab and a lintel band. Most houses with lintel bands performed very well (Figure 8).

Reinforced concrete frame buildings

Many RC frame buildings (up to four storeys) with brick masonry infill walls characterized by simple and regular configuration, performed well even though most of these were not formally designed, and certainly not for seismic loads. The common form of damage included separation cracks at the interface of the RC frame and infill panels, and cracking of infill material.

Figure 7. Collapse of one of the wythes in a traditional house in slate wafer masonry.

Implications for the high dam at Tehri

Construction of the 260 m high rockfill dam at Tehri, located between the MCT and the MBT (Figure 1) has remained controversial since its inception. The environmental issues associated with the dam as well as the seismic design parameters have remained active topics of discussion[19–24]. Occurrence of another earthquake in its vicinity is likely to enliven this debate. In this context, it may be useful to review some of these issues.

Although no great earthquakes have been reported from the vicinity of the dam during the historic past, the Uttarkashi and the Chamoli events have occurred during a span of nine years, within a radius of ~ 125 km from Tehri (Figure 1 *b*). As mentioned earlier, the largest historic earthquake in this region is the 1803 event of $M > 7$. Maximum intensity based on historic reports[18] indicates that the source of this earthquake may be within a distance of 50 km from the dam. Aside from current and historical activity, this region is believed to have undergone several movements in the recent geological past, as expressed by the morphological features like deep incision of rivers and development of river terraces[24]. The WNW–ESE trending Srinagar Thrust is a prominent structure reported to be passing through the vicinity of the dam[24]. Data on slip rates or fault offsets in trenches are not available, placing major limitations on the evaluation of recurrence rate of

Figure 8. Two-storey house at Pipalkoti showing no damage. The ground storey is in slate wafer masonry, upper storey in concrete block masonry has been added later. Both storeys have RC lintel band.

earthquakes in this region. However, probability for an earthquake during the projected life of the dam is considered to be high[21,25].

Effect of impoundment of a large reservoir leading to the possibility of reservoir-induced seismicity (RIS) is another concern. Proximity to an active thrust and geological conditions favourable for infiltration of water into the deep fault zones may favour weakening of faults, leading to failure[20]. Gupta and Rajendran[26] suggested that the water load might tend to stabilize the thrust faults in the immediate vicinity of the Himalayan reservoirs, making them less prone to seismicity, although the delayed effect of pore pressure diffusion may be significant during later periods. Mathematical simulation for the load-induced changes at Tehri has also suggested a postponement of the next earthquake[27], but later studies suggest that the delay may be short-lived[28]. Thus, the studies so far indicate that water-induced weakening of the faults may remain as a point of concern in the long-term life of the dam.

Another important issue is the possibility of landslips, earthquake-induced or otherwise. A large chunk of land falling into the river could generate large waves that could breach the dam or could cause an overflow. Instances of landslips that caused enormous floods in the Indus River in Pakistan are reported[19]. The landslips and rockfalls that followed a moderate earthquake at Chamoli (that too during a dry season) underline the serious threat posed by these processes and an urgent need to identify landslide prone regions, from the point of seismic hazard associated with high dams in the Himalaya.

Need for a database

A major issue of contention regarding the Tehri dam has been the choice of peak ground acceleration (PGA). Preliminary design of the dam was carried out by pseudo-static analysis for a design seismic coefficient of 0.12 g. Subsequently, dynamic analyses were carried out for earthquake motions with effective peak ground acceleration (EPGA) of 0.25 g, which was considered inadequate by many workers[19,21,22]. Specialists from Russia have also been involved in the evaluation of the seismic hazard at the dam site and checking the dam's safety. After considering a number of postulated earthquake scenarios, their evaluation of dam safety was based on two worst ground motions: a *M* 6.5 earthquake on Srinagar fault with PGA of 0.5 g at Tehri site, and a *M* 8.0 event on the MBF with PGA of 0.4 g (ref. 29). At the time the dam was designed, strong motion records were not available for this region, and the characteristics of strong motion records obtained elsewhere were used to develop the design spectrum. Data on stress drop, attenuation characteristics and site amplification have also been very limited, for a proper evaluation of the seismic hazard
in the Tehri region. In this context, the earthquake at Chamoli is significant as it provides a useful set of data.

Summary

The Chamoli earthquake gives further credence to the view that the frontal parts of the MCT are still active and capable of generating moderate/large earthquakes. From this point, more studies in the epicentral region may be useful in identifying and characterizing the active faults in the region. Our studies indicate that it may be possible to identify sites showing tell-tale signatures of active tectonism in these areas, in order to quantify the slip rate. A moot point is whether the faults in Chamoli and Uttarkashi are multiple segments of a single structure, and if an earlier earthquake occurred in 1803 and had ruptured both these segments, resulting in a larger stress drop. If we assume this as the real scenario, it is likely that the large and moderate earthquakes in the Garhwal–Kumaun region follow a different rate of recurrence.

Our studies suggest that the historic temples in the area, which are among the oldest surviving structures, can be used as archives of preserved evidences of past earthquakes in the region. A systematic study of these temples may be useful to reconstruct part of the earthquake history of these regions. The 1803 earthquake appears to be a larger event ($M > 7$), which seems to have affected a wider area, in comparison to the Uttarkashi and Chamoli earthquakes.

From an engineering point of view, damages due to the Chamoli earthquake clearly demonstrated that codal provisions for masonry houses are quite effective. While the traditional stone houses failed as expected, constructions with lintel bands performed well. Settlements developed on alluvial terraces, although far separated, suffered severe damages, while the intervening regions on relatively harder rocks suffered little or no damage. Site-amplification could be one of the probable reasons for wider damages during the 1991 earthquake at Uttarkashi, which is situated on extensive river terraces. The Chamoli earthquake provides a whole set of new data, including new ground motion data to study the seismic attenuation and site amplification characteristics, for better hazard assessment and mitigation.

1. Jain, S. K., Murty, C. V. R., Arlekar, J., Rajendran, C. P., Rajendran, K. and Sinha, R., Special Report, Earthquake Engineering Research Institute (EERI), California, 1999, vol. 33, pp. 1–8.
2. Khattri, K. N. and Tyagi, A. K, *Tectonophysics*, 1993, **96**, 281–297.
3. Bilham, R., *Curr. Sci*., 1995, **69**, 101–127.
4. Gansser, A., *Geology of the Himalayas*, Interscience, New York, 1964, p. 289.
5. Molnar, P. and Chen, W. P., in *Mountain Building Processes* (ed. Hsu, K. J.), Academic Press, New York, 1982.
6. Le Fort, P., *Am. J. Sci*., 1975, **275**, 1–44.
7. Molnar, P., Chen, W. P., Fitch, T. J., Tapponier, P., Warsi, W. E. K. and Wu, F. T., *Editions C.N.R.S.*, 1977, **268**, 269–294.
8. Seeber, L. and Armbruster, J., in *Earthquake Prediction: An International Review*, Maurice Ewing Series 4, AGU, Washington, DC, 1981, pp. 259–277.

9. Ni, J. and Barazangi, M., *J. Geophys. Res.*, 1984, **89**, 1147–1163.
10. Chander, R., *Tectonophysics*, 1988, **149**, 289–298.
11. Yeats, R. S. and Thakkur, V. C., *Curr. Sci.*, 1998, **74**, 230–233.
12. Pandey, M. R., Tandukar, R. P., Avouac, J. P., Lave, J. and Massot, J. P., *Geophys. Res. Lett.*, 1995, 751–754.
13. Khattri, K. N., Chander, R., Gaur, V. K., Sarkar, I. C. and Kumar, S., *Proc. Indian Acad. Sci.* (*Earth Planet Sci.*), 1989, **98**, 91–109.
14. Cotton, F., Campillo, M., Deschamps, A. and Rastogi, B. K., *Tectonophysics*, 1996, **258**, 35–51.
15. Valdiya, K. S., *Geology of Kumaun Lesser Himalaya*, Wadia Institute of Himalayan Geology, Dehra Dun, 1980, p. 291.
16. Powers, P. M., Lillie, R. J. and Yeats, R. S., *Bull. Geol. Soc. Am.*, 1998, **110**, 1010–1027.
17. Ballore, M., *Mem. Geol. Surv. India, Calcutta*, 1904, **35**, 153–194.
18. Smith, R. B., *J. Asiatic Soc. Bengal*, 1843, **12**, 1029–1056.
19. Pearce, F., *New Sci.*, 1991, **26**, 37–41.
20. Valdiya, K. S., *Curr. Sci.*, 1992, **61**, 801–803.
21. Brune, J. N., *Tectonophysics*, 1993, **218**, 281–286.
22. Iyengar, R. N., *Curr. Sci.*, 1993, **65**, 384–392.
23. Chander, R. and Kalpna, *Curr. Sci.*, 1996, **70**, 291–299.
24. Valdiya, K. S., *High Dams in the Himalaya*, PAHAR, Nanital, 1993, p. 40.
25. Chander, R., *J. Struct. Geol.*, 1992, **14**, 621–623.
26. Gupta, H. K. and Rajendran, K., *Bull. Seismol. Soc. Am.*, 1986, **76**, 205–215.
27. Chander, R. and Kalpna, *Curr. Sci.*, 1996, **70**, 291–299.
28. Chander, R., Kalpna and Gahalaut, V. K., *Curr. Sci.*, 1996, **70**, 873.
29. Thatte, C. D., *Indian Geotech. J.*, 1992, **22**, 1–41.

ACKNOWLEDGEMENTS. This study forms part of a DST sponsored project at CESS, Thiruvananthapuram and another at IIT, Kanpur, funded by the Ministry of Human Resources Development. It was also partially funded by the Earthquake Engineering Research Institute, USA. We thank IMD for the aftershock data, and the district officials at Gopeshwar for support during the fieldwork. Comments from three anonymous reviewers have been helpful in revising the paper.

Received 14 June 1999; revised accepted 13 October 1999